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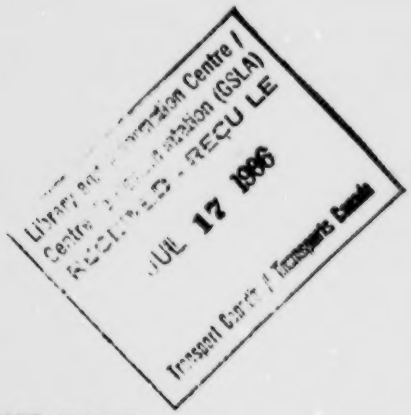
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ON-BOARD POWER SOURCES FOR FREIGHT CARS

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17. Abstract

The moving freight car is examined to determine the sources of available energy that might be used to generate small quantities of on-board electric power, exclusive of conventional generators mechanically linked to the wheels or axles. Energy conversion techniques appropriate for the sources are assessed with respect to their suitability for the rail environment and dependence on track and operating conditions. These techniques include electrodynamic and piezoelectric devices by truck vibration, thermoelectric generators using bearing heat, turbines driven by the apparent wind due to motion, radioisotope thermoelectric generators (RTGs) and solar cells. RTGs meet all guideline requirements but are expected to be expensive because of the strictly regulated plutonium fuel. Solar energy is a very attractive solution. Wind power is adequate, but the wind turbine would require protection against vandalism, foreign objects and weather. Vibration-driven systems are considered impractical, while bearing heat is suitable only as a low power (100 MW) source. Recommendations are made.

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17. Resume

Ce rapport étudie le wagon de marchandises en mouvement sous l'angle des possibilités qu'il offre de produire de l'électricité en faible quantité pour alimenter certains appareils de bord, les génératrices classiques entraînées par les roues ou les essieux étant exclues au départ. Il évalue les diverses méthodes de conversion possibles par rapport à leur adaptabilité au contexte ferroviaire et la mesure dans laquelle elles dépendent de l'état de la voie et des conditions d'exploitation. Parmi les matériels envisagés mentionnons les dispositifs électrodynamiques et piézoélectriques asservis aux vibrations des essieux, les génératrices thermoélectriques utilisant la chaleur émise par des radioisotopes ou existant dans les boîtes d'essieux, les turbines mues par le vent apparent dû au mouvement et les cellules solaires. Il fait observer que les génératrices thermoélectriques radioisotopiques satisfont à toutes les conditions fixées, mais qu'elles coûteront cher du fait que le plutonium, qui est le combustible nucléaire utilisé, fait l'objet de réglementations rigoureuses. La solution solaire est très intéressante. La solution éolienne l'est un peu moins, d'autant plus qu'il faudra protéger l'éolienne contre le vandalisme, les chocs et les intempéries. Il montre que les systèmes asservis aux vibrations des essieux sont de réalisation difficile et que la conversion de la chaleur existant dans les boîtes d'essieux ne produit que de l'électricité de faible puissance (100 mW). Le rapport termine en formulant certaines recommandations.

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SUMMARY

The introduction of electronic systems for monitoring, hazard warning and brake control on freight cars would require on-board power at the individual cars. Transmission lines running the length of the train must have a highly reliable inter-car connector, which means an additional coupling-up operation and loss of part of the transmission system if a break in continuity occurs. The objective of this study was to identify, describe and assess electric power generating techniques which could exploit the energy available at each car on a moving train. Mechanically linked conventional generators and alternators are not considered to be suitable because of their high maintenance requirements as well as the inconvenience they create for truck maintenance.

Operational guidelines have been developed in order to make realistic assessments. The principal electrical requirement is an average power delivery of 1 watt. Mechanical specifications restrict the power generator to 15 kg. In addition to withstanding the accelerations and environmental conditions met on freight trains, certain undesirable characteristics must be avoided, such as mechanical connection to the wheels or axles, bleeding of air from the brake line, contact with the rails or ground, and hazards to personnel.

Sources of power on the moving train were evaluated along with radioisotope heat sources and solar energy. Large amounts of power were found to exist in the heat of the bearings, vibration of the suspension, and apparent wind due to motion. However, the efficiency with which the energy can be extracted was found to be low in practice.

Energy conversion techniques appropriate for extracting the available power were assessed with respect to their suitability for the rail environment and dependence on track and operating conditions. These techniques include electrodynamic and piezoelectric devices driven by truck and suspension vibration, thermopiles using bearing heat, turbines driven by the air flow due to train motion, radioisotope-thermoelectric generators (RTGs) and solar cells.

The only electric generating technique to meet all guideline requirements is the RTG, but these devices are expected to be expensive because of the strictly controlled plutonium fuel. There may also be an acceptability problem. Solar energy is a very attractive solution requiring less than 0.5 m^2 of solar panel. However, the panels must be protected and 15 to 30 days battery storage is needed. Wind power is adequate but wind turbines would have to be protected against vandalism, foreign objects and weather. The need for moving parts makes them less reliable and more maintenance prone than other systems examined. Vibration-driven systems are considered unsuitable for further development because the driving mechanism will become less effective as improvements in track condition and trucks are made in order to reduce fuel consumption. Bearing heat is suitable only as a

low power source, of the order of 100 milliwatts, because of the large contact surface needed on the bearing casing and the low differential temperature under normal operating conditions.

The main recommendations are that RTGs be considered for use on end-of-train-units (ETUs), perhaps with a less toxic radioactive fuel. Solar panels should be given serious further consideration. The commercial products, which exist already, should be field tested to determine whether they have adequate ruggedness or, if not, where improvements are needed. Wind turbines with innovative protective housings should be explored further with attention directed to the inherent aerodynamic characteristics of the freight car. Vibration-driven systems should not be developed further and thermoelectric devices should be considered only for low power applications, keeping in mind the 20 to 60 minute warm-up time needed. Since all but the RTG require energy storage, battery technology will have to be investigated with attention to long-life, low-temperature operation in a highly vibrational environment.

SOMMAIRE

L'introduction de systèmes électroniques de surveillance, d'alerte et de freinage automatiques à bord des trains de marchandises nécessite des sources d'énergie individuelles. Les circuits transmettant des signaux d'un bout à l'autre du train doivent être connectés les uns aux autres par un dispositif hautement fiable, ce qui entraîne des opérations de couplage et sous-entend des pertes d'information en cas de rupture dans la continuité électrique. Cette recherche avait pour objet de trouver, de décrire et d'évaluer des sources d'énergie électrique susceptibles de tirer parti de l'énergie développée par les wagons en mouvement. Au départ, les génératrices et les alternateurs classiques entraînés mécaniquement ont été exclus du fait qu'ils nécessitent beaucoup d'entretien et qu'ils gênent celui du bogie.

Des critères prévus ont été fixés afin d'autoriser des évaluations cohérentes; la plus importante a été la production d'une puissance moyenne d'un watt. Parmi les autres exigences formulées, figurent celles du poids maximal de 15 kg, de sécurité, de résistance aux accélérations et à l'environnement particulier au domaine ferroviaire et l'exclusion de caractéristiques telles que; entraînement mécanique par les roues ou les essieux, soutirage d'air de la conduite générale de freinage et contact avec les rails ou le sol.

Les sources d'énergie offertes par les wagons en mouvement ont été évaluées parallèlement à la thermoélectricité radioisotopique et solaire. D'importantes sources d'énergie existent à bord : chaleur dans les boîtes d'essieux, vibrations dans la suspension et force du vent apparent dû au mouvement. Mais les procédés de conversion ont été trouvés peu efficaces.

Ces procédés ont tous été évalués par rapport à leur adaptabilité au contexte ferroviaire et à la mesure dans laquelle ils dépendent de l'état de la voie et des conditions d'exploitation. Ont été envisagés : les dispositifs électrodynamiques et piézoélectriques asservis aux vibrations des essieux et de la suspension, les matériels thermoélectriques utilisant la chaleur dans les boîtes d'essieux, les turbines mues par le vent dû au mouvement du train, les génératrices radioisotopiques et les cellules solaires.

Le seul matériel ayant satisfait à toutes les conditions a été la génératrice thermoélectrique radioisotopique; mais, d'une part, sa réalisation coûte cher du fait que le plutonium fait l'objet de réglementations rigoureuses, et d'autre part, il n'est pas certain que l'on accepte volontiers l'utilisation de l'énergie nucléaire dans cette application. La formule solaire est très intéressante car un capteur de moins d'un demi-mètre carré suffit par wagon; toutefois, elle a l'inconvénient de la fragilité des capteurs et la nécessité de stocker

l'énergie produite. La solution éolienne est bonne, mais il faudra protéger l'éolienne contre le vandalisme, les chocs et les intempéries; de plus, les pièces mobiles qu'elle nécessite la rendent moins fiable et plus exigeante en entretien que d'autres matériels envisagés. Les systèmes asservis aux vibrations perdent progressivement de leur efficacité à mesure que l'état de la voie s'améliore et que les bogies se modernisent dans le but de réduire la consommation. Efin, la conversion de la chaleur dans les boîtes d'essieux ne produit que de l'électricité de très faible puissance, de l'order de 100 mW, parce que le différentiel thermique est bas dans les conditions normales de fonctionnement; pour une puissance plus grande, il faudrait des échangeurs de chaleur trop encombrants.

Le rapport recommande en premier lieu les génératrices thermoélectriques radioisotopiques utilisant comme source de chaleur un combustible peut-être un peu moins dangereux que le plutonium. Vient ensuite le matériel solaire dont il existe déjà sur le marché de nombreuses variantes; mais il faudra en vérifier la robustesse en service et peut-être l'améliorer par des perfectionnements. Les turbines éoliennes sous carter protecteur étudié spécialement devraient faire l'objet d'une recherche plus poussée, prenant en compte le comportement aérodynamique particulier des wagons. Le rapport recommande, en outre, d'écarter les systèmes asservis aux vibrations et de ne s'arrêter à la conversion de la chaleur dans les boîtes d'essieux que pour des utilisations de faible puissance, sans oublier la contrainte du temps de réchauffement qui peut varier entre 20 et 60 minutes. Enfin, étant donné que tous les procédés, à part la thermoélectricité radioisotopique, nécessitent un stockage de l'énergie produite, la recherche devra porter également sur les accumulateurs et, notamment, sur leur durabilitié et leur résistance aux basses températures et aux fortes vibrations.

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1. BACKGROUND

The efficiency, safety and reliability of freight trains could be greatly improved by the implementation of electronic monitoring and control systems within the train consists. Monitoring and hazard warning could, in many cases, increase safety and reduce maintenance costs by providing early identification of component deterioration. Reliable monitoring of brake operation would save time and manpower in checking out trains, while stress sensors throughout the train would allow optimium control to be applied to the train as a whole. Electrical control of pneumatic brakes would contribute to the more effective use of rolling stock by allowing the formation of longer trains moving at higher speeds, while reducing the wear and tear on coupler components.

Electronic monitoring and control equipment on individual cars requires a reliable power source at each car. One obvious solution would be the train-length transmission line, or train line. However, despite its simplicity, the train line possesses several unattractive features:

- every car in the consist must be outfitted with the transmission line
- a highly reliable, rugged, inter-car connector is needed and experience suggests that the maintenance of electrical continuity would be a very serious problem
- a train line would introduce an additional coupling-up and uncoupling operation.

The other obvious solution is batteries. Here the problem areas are the lifetime in the case of primary (non-rechargeable) cells and the need to provide a means for recharging or maintaining charge in the case of secondary (rechargeable) cells. Two examples of these situations are:

- one of the proposed automatic vehicle identification (AVI) devices which operates on a 15 to 20 year lithuim cell
- the end-of-train units (ETU) which employ rechargeable nickel-cadmium batteries with a 400-hour service interval between recharges.

While an economical, reliable, rugged, environment-proof, low-power electric source could be beneficial to the AVI and ETU systems by extending their operating lifetimes and reducing maintenance, such a power source will be essential to the widespread use of electronic systems on freight cars in general.

In a previous report on signal and power transmission technology for use on freight trains [Aitken (1982)] it was suggested that independent on-board power sources would open the door to some quite attractive cab-to-car communications concepts. The report recommended an investigation of possible energy conversion concepts and an assessment of the state of the necessary technology. That recommendation led to the initiation of the study reported here.

2. OBJECTIVE AND SCOPE

The objective of this project is to identify, describe and assess power-generating techniques which might have potential as low-power sources of electricity on freight cars.

To achieve this objective it was first necessary to develop operational guidelines for a small, rugged, reliable, maintenance-free power source for freight cars through discussions with personnel from Canadian National (CN) and Canadian Pacific (CP) Railways. Information on energy conversion and the energy available at a freight car was collected from the technical literature, manufacturers of relevant products and personal interviews. An extensive search of the INSPEC data base found a large number of relevant technical articles and reports which were subsequently obtained. Power-generating possibilities and technology options were identified from the information collected. The options identified have been assessed on the basis of technical and environmental suitability to the freight-car application. Recommendations have been made.

No experimental work was proposed in this project, nor was the intention to design a specific system or device. Although energy storage devices are necessary in order to provide continuous power in all but one of the generating schemes studied, batteries and storage technology are not included in this study.

3. OPERATIONAL REQUIREMENTS

In order to make a realistic assessment of the relevant technologies, a set of guidelines was developed in consultation with personnel at CN and CP. These guidelines:

(a) define the likely power requirements that an on-board source would have to satisfy

(b) identify the thermal, mechanical, environmental and safety constraints that an acceptable system must meet.

They are presented as a frame of reference for this study and are not to be considered as product specifications for an eventual system or device.

3.1 Operational Guidelines

(A) **Electrical**

Maximum voltage: 74 V dc, 74 V rms ac (this limit is based on safety considerations)

Estimated power requirements:

(a) Electronic circuits: average = 0.5 watts

Radio transmitters: peak = 10 watts, average < 1 watt

(b) Electro-pneumatic brake control: peak = 20 watts for 0.01 seconds; average = 0.2 watts if the electro-mechanical device is activated once per second.

Estimated requirement: 30 watts peak, 1 watt average.

(B) **Mechanical**

- Maximum dimensions should not exceed 25 cm x 50 cm x 50 cm. A flat package is preferable.
- Maximum weight should be 15 kg or less including package.
- One man should be able to handle the power-source package for initial mounting and for subsequent servicing.

- Vibration, shock and impact resistance must conform to the requirements demanded of other electronic equipment used on-board, such as the End-of-Train Units.

Guideline values are:

Vibration: along any axis, withstand ± 0.5 g per Hz in the frequency range 0-6 Hz; ± 3.0 g in the frequency range 6-500 Hz.

Shock: Withstand 10 g peak shock for 20 milliseconds, along any axis.

Impact: Withstand a 2 metre drop to a concrete floor.

Note that these values assume that the unit is mounted on the car body. If a truck side frame location is used, much higher shock and vibration resistance would be required. Accelerations of 50 to 100 g lasting for up to 2 m sec. have been measured on truck side frames of trains moving 30 mph.

(C) **Environmental**

Temperature: Deliver minimum required power over the temperature range -40°C to +70°C (-40°F to 158°F).

Altitude: 3600 m (12,000 ft)

An acceptable system must be either sealable against, or inherently unaffected by, moisture, fog, dirt, dust, saline solutions and other corrosive chemicals. This will be primarily a matter of packaging.

(D) **Undesirable Characteristics**

- Mechanical connections to the wheels or axles.
- Contact with the rails or the ground.
- Bleeding of air from the brake air line.
- Electromagnetic radiation from the power source of sufficient strength to interfere with other electronic systems.
- Interference with existing on-board equipment.
- Hazards to personnel as, for example, from explosion or radioactivity.

Most of the environmental and mechanical constraints would be satisfied through suitable packaging of a power source, and do not reflect inherent properties demanded of the power-generating technology. However, it will be important to assess whether technologies would be amenable to rugged, environmentally secure packaging.

Some further comments are in order regarding item (D). Power sources, such as conventional rotating electric generators or alternators, driven by mechanical linkages to wheels or axles would add greatly to the maintenance requirements of freight cars. There is sufficient experience in the railway industry with generators on passenger cars and special-purpose freight cars to rule out such systems immediately. Furthermore, the size, weight and strength needed in the mechanical components to ensure an adequately rugged system would be out of proportion to the electric power needed. Similarly, systems based on a ninth wheel or other devices contacting the ground or rails would be a source of maintenance problems and quite vulnerable to damage. While there is a large amount of power available in the air-pressure system which operates the brakes, it is generally considered unwise to tamper with the brake line. The tapping junctions and the generating equipment driven from them may introduce unforeseen effects into the brake control system with potentially disasterous consequences. Therefore, the use of air from the brake line has been ruled out for the purposes of this study.

4. POSSIBLE SOURCES OF POWER

4.1 Available Power

Before addressing the matter of the energy-conversion technology that might be used on freight cars, it is important to identify the possible sources of power on a car and to estimate the likely levels of available power. Appendix A identifies the usable sources, discussing their important characteristics, and gives estimates of power and other pertinent parameters. Only a brief summary is given below for the case of a 40-ton car travelling at 40 km/h (25 mph).

(1) Roller bearing heat, which varies as $(\text{velocity})^{3/2}$ and $(\text{weight})^{1/3}$, would provide 350 watts per bearing. Because of the low temperature of the bearings, about 10 per cent of this power is theoretically extractable.

(2) Energy dissipated in the suspension is vibrational energy which is proportional to weight and (velocity)^2. Dissipation per truck on class 4 track would be 1,250 watts, but would drop to 78 watts on class 6 track.

(3) The apparent wind created by the forward motion of the train contains 838 watts/m^2 at 40 km/h (25 mph). But the available power varies as (velocity)^3 so that at 8 km/h (5 mph) the power would be 6.7 watts/m^2.

(4) Other on-board sources examined and rejected were drawbar action, brake heat and heat in the suspension.

(5) Radioisotope heat sources and solar radiation are also examined. A few grams of plutonium can produce 17 watts of thermal power. The average insolation on a horizontal plate in Southern Canada is approximately 4,000 Wh/m^2 per day.

4.2 Power Source Location

The location of the power source refers to where the energy-extracting apparatus may or must be located. In order to extract energy from hot bearings or suspension vibrations, the power-supply device must be on the truck. Thus, the device itself is subjected to the vibrations and shocks which can be 10 times higher than the vibrations on the body. A truck-mounted device would have to be connected to electrical apparatus on the body by means of an electric line which would have to be readily disconnectable so as not to hamper truck replacements. Electric cabling will be vulnerable to damage and will be an important factor in the reliability of the power supply. Truck-mounted systems would be appropriate for the powering of bearing, wheel and brake monitors. Mounting of a device on the body is considered an advantage in this study because the primary monitoring, transmission systems and brake control systems for which the power is needed would be on the body.

4.3 Storage

All of the systems studied, except the radioisotope heat source, have some degree of intermittance in their power delivery. For example, variations in train speed, load and track conditions will affect the

amount of power delivered. Therefore, it is assumed that the power sources will not deliver power directly to electronic circuits, but will charge a battery of some sort or some other type of storage device such as capacitors.

The energy that can be drawn from a rechargeable battery is always less than the energy delivered to it during charging. This property is represented by the energy efficiency, which for conventional lead-acid batteries is about 70 per cent. No attempt has been made to include a factor for charging efficiency because the numerical value will be specific to the type of cell, depth of discharge permitted, characteristics of the charging source and other factors which are not yet defined.

5. ENERGY CONVERSION TECHNIQUES

This section identifies techniques which might be employed in an on-board power supply. Details of the principles of operation, mathematical analyses, application examples and a summary of advantages/disadvantages are given in the appendices indicated in each case.

5.1 Linear Electrodynamic Converter

The principal components of a linear, electrodynamic, energy converter are a spring-mass mechanical system, and an electrical system consisting of a coil of wire and a magnet which can move relative to each other. The electrical and mechanical systems are coupled either by using the magnet as the mass, or by mounting the coil on the mass while keeping the magnet fixed. A detailed analysis of the mechanical and electrical dynamics of this type of converter is given in Appendix B. The term "linear" is used to distinguish the oscillating magnet/coil system from the conventional rotating generator or alternator.

Vibration is the energy source for a linear electrodynamic converter. Its peak output voltage is proportional to the peak velocity induced in the magnet relative to the coil, and the back emf reaction between magnet and coil when a current flows through an external load is the damping force experienced by the mechanical system.

5.2 Piezoelectric Energy Converters

Piezoelectricity is the name given to a phenomenon found in certain asymmetrical crystals and some ceramic materials. When piezoelectric materials are subjected to a force, charges are displaced by the resulting deformation of the crystals and a potential difference appears across the crystal. The forces must be applied along specified axes for the phenomenon to occur. It is also reversible in that application of a voltage will cause a deformation of the material. Piezoelectric materials have found application in hydrophones, high voltage generators and many sensing devices for measuring accelerations, impacts and strains. A configuration, called bimorph, has two thin strips of piezoelectric material bonded together along their contact faces with the polarities of the strips reversed. When the strip is bent, large stresses occur along the interface. Bimorphs are essentially a technique for increasing the voltage/unit deflection or displacement of the piezoelectric material. Devices based on bimorphs include the "ceramic" phonograph pickup, "ceramic" microphones and headphones. Recently, some man-made polymeric materials have been given piezoelectric properties. Most notable is PVF^2 (poly (vinylidene fluoride)), which has been used in the bimorph mode.

Piezoelectric converters are realized in three principal mechanical configurations which will be called the accelerometer mode, the compression mode and the bending mode. In the accelerometer mode the piezoelectric material is sandwiched between a base and a mass. When the base is accelerated the inertia of the mass creates a force on the material, either compressive or tensile depending on the direction in which the base is accelerated. In the compressive mode the material is "squeezed" by a mechanical system which provides some form of leverage. The bending mode applies to the bimorph structure mentioned above.

A more detailed discussion of the piezoelectric converter, some pertinent properties of common piezoelectric materials and the analysis of the energy conversion mechanism are given in Appendix C.

5.3 Thermoelectric Converters

Thermoelectric conversion is based on a physical phenomenon, called the Seebeck effect, in which, when a temperature difference exists between the ends of a metal or semiconductor, a potential difference occurs between the ends. This potential difference is directly proportional to the temperature difference. The most familiar form of the thermoelectric converter is the thermocouple which is used in temperature measuring devices and thermostats. Since individual thermocouples are capable of delivering only low power of the order of milliwatts, they are combined in arrays called thermopiles when larger powers are needed. Thermopiles have been used for many years as power sources in space, military and industrial applications. Heat sources have been radioisotopes, fossil fuel or waste heat from engines. A significant thermoelectric industry exists today. Thermoelectric converters have proven themselves to be rugged, reliable and maintenance-free in harsh environments, and are often the preferred choice of power generation when reliability is paramount and a heat source is available. Appendix E gives some further application examples, the characteristics of some current semi-conductor thermoelectric materials, and the analysis of a thermoelectric generator in the context of the freight-car application.

5.4 Wind-Powered Generators

The forward motion of the freight car through the air creates an apparent wind blowing in the opposite sense to that of the car motion. If local drag and other aerodynamic effects at the surface of the car can be ignored, the wind speed is the speed of the car. Because propeller and turbine wind-energy converters operate at winds of from 10 to 50 km/h, wind power is worth exploring as an on-board source. The characteristics of a variety of propellers and turbines, along with their advantages and disadvantages, are discussed in Appendix D.

5.5 Radioisotope-Thermoelectric Generators

The radioisotope-thermoelectric generator (RTG) concept has been used extensively in satellites and space vehicles to provide 100s of watts of electrical power with a high degree of reliability. RTGs have also

been used to power remote radio relays, weather monitors and submarine monitoring stations on the ocean bottom [Bennett et al (1983), Rosell and Vogt (1978)]. However, the RTGs of interest to the freight car application are the units delivering ½ to 2 watts, sometimes referred to as nuclear batteries. Details of a commercially available RTG and a discussion of its application are given in Appendix F.

5.6 Solar Power

With the sun overhead, the power available in the sunlight reaching the earth's surface is 1 kW/m^2. The light energy can be converted to electricity by means of the photovoltaic effect. Semiconductor devices based on this effect are called solar cells. In order to increase the collecting area beyond that of a single cell, a large number of cells can be mounted together and interconnected in what is known as a solar array or solar panel. Solar cell manufacture is a well-developed industry whose product is still developing and improving. Further developments are expected to increase efficiencies and reduce costs. The continued development of solar-energy conversion technology is driven by the interest in electricity from sunlight shown by industry, the military and the space programs. Solar power has already been used by the railways to operate track circuits in remote areas where conventional ac power is not accessible, and Norfolk Southern Railway has installed solar panels on cabooses to recharge batteries. Appendix G provides further details.

6. ASSESSMENTS

The technical factors considered in assessing the merits of the various electric power generating schemes are outlined below:

(1) **Speed dependence.** If the output power depends on speed to the power n (v^n), a value of n greater than unity will mean a rapid decrease in output as speed drops, while n less than unity will mean a slower drop. Systems dependent on speed obviously give no output at zero speed and generally do not give useful outputs at low speed.

(2) **Weight dependence.** The power available from vibration- and friction-generated heat depends on weight. Full cars will provide a greater available power than will empty ones. It seems reasonable

that an on-board power source should provide adequate power when the car is empty. In making numerical comparisons a 40-ton car has been used.

(3) **Track dependence.** Only the systems which depend on vibration are directly dependent on track condition. Data for FRA class 4 and class 6 tracks have been used in the calculations. In each case the values used represented the largest track profile variations allowed within the class. A fundamental problem with systems which depend on track condition is that the better the track, the poorer the power delivery. Techniques dependent on train speed have an indirect dependence on track condition in that the rougher the track the lower will be the maximum train speed.

(4) **(a) Location.** Some energy-conversion devices must be mounted on the truck, some can be on the truck or the body, while others are practical only on the body. In this study a body location is considered preferable. Truck-mounted devices delivering power to systems on the car body will require cabling, protective flexible conduit and reliable connectors to facilitate replacement of trucks. However, a truck location would be of interest for the powering of sensors or other electronic equipment mounted on the trucks.

(b) Power and source impedance. Electric power deliverable from the available power source is a primary consideration. The objective is an average power of 1 watt. Calculations have been based on a device fitting within the size and weight constraints imposed by the guideline operation requirements of Section 3, a train speed of 40 km/h when speed is a factor and a weight of 40 tons when weight is a factor. Power alone is not the only electrical parameter that needs to be considered. The voltage at which the power is delivered and the internal source impedance are also important practical aspects. A high-voltage/high-impedance system will in general be difficult to apply to the driving of low-voltage electronic systems.

(5) **Power-delivery mode.** This characteristic concerns the manner in which the electrical energy is delivered. For comparison purposes, the following terms have been defined: "steady" means that the power delivered is constant for a given load

resistance and minimally affected by external factors, as would be the case with a good battery; "intermittent" means that the power delivered could vary considerably along the railway, perhaps dropping to zero at times or occurring in bursts; "continuous" means that a steady power is available as long as the primary source (vibration, heat, wind, etc.) is active; "variable" means that the power delivered is dependent on external factors and, for example, could vary from route to route, from day to day, with climatic conditions or loads. Generating mechanisms by their nature may give alternating current (ac) or direct current (dc).

(6) **Ruggedness and sealability** Ruggedness has been assessed by reference to the physical robustness of existing products based on the same principles of operation. It is by its nature qualitative and subject to significant variation with product cost and the specific embodiments. A sealable device is one which can be completely enclosed in a strong, weatherproof container with only the electrical conductors communicating between the inside and the outside of the container.

(7) **Reliability.** Potential reliability has been assessed by observation of the same concepts and devices in other applications. Unfortunately, the railway environment is unique with respect to physical abuse of equipment, mechanical shock and vibration, and dirt. Thus, comments on reliability must be somewhat speculative.

(8) **Failure mode.** In some instances the most likely manner in which a system will fail or be rendered inoperative can be predicted.

(9) **Technology and complexity.** A "highly developed" technology means that the properties of the materials and the principles of operation are well understood and widely used in other applications. It implies that an adequate industry exists to manufacture a product. "Developing" technology means that the applications of the techniques or materials are still evolving. "Experimental" means that technology is still at the laboratory stage.

(10) **Energy source.** This refers to the primary driving mechanism of the energy converter on the freight car.

(11) **Energy storage requirements.** Because of intermittency, variability and delay in the delivery of power with most of the systems, some form of storage is necessary if a steady power supply is to be available for operating electronic equipment. For short-time constant intermittency, capacitors may suffice. However, delay and longer-term variability will require batteries which can be charged during the times that adequate power is being generated.

(12) **Installation and packaging.** This topic addresses the question of whether the energy conversion system can be a simple added-on device, with suitable wiring understood, or whether alterations to the car, or components of the car, are necessary for implementation of the generator.

(13) **Temperature.** The temperature range has been deduced from the properties of the materials and the characteristics of any other known devices using the same principles of operation.

(14) **Costs.** Rough estimates of device costs have been made by considering the prices of similar commercial products and by pricing the key components of the devices considered here. Where manufacturers' prices were obtained, they were for lots of 1,000 units.

Table 6.1 is an overview of the factors affecting the assessment of the various techniques.

7. CONCLUSIONS

The conclusions to be drawn from this study are as follows.

(1) The sources of available and accessible energy on a freight car are suspension vibration, bearing heat, and apparent wind from the forward motion of the train. These sources represent quantities of power well above the amount proposed in the guideline requirements. However, the efficiency with which this power can be converted to electricity is not high. Available sources independent of the freight car are radioisotopes as producers of heat and solar energy.

TABLE 6.1

ASSESSMENT SUMMARY

	1	2	3	4	5	6/7
	Dependence on			Location Power (Source Resistance)	Power Delivery Mode	Ruggedness, Reliability & Sealability
	Speed	Weight	Track			
Linear electro-dynamic	v^2	W	Strong	Truck 12 W Body 1.2 W (low)	(ac) Intermittent and variable	Potentially rugged and reliable, but moving parts. Sealable.
Piezoelectric				Truck		
Accelerometer (ceramics)				0.35 mW (10^7 ohms)		Rugged and reliable. Completely sealable.
Compression (ceramics)	v^2	W	Strong	1 W (10^9 ohms)	(ac) Intermittent and variable	Rugged and reliable. Possibly needs moving parts & linkages.
Bimorph (PVF_2 polymer)				mWs (10 ohms)		Uncertain. Sealable
Thermoelectric (bearing heat)	$v^{1.5}$	$W^{1/3}$	Indirect	Truck, 1 W (1-10 ohms)	(dc) Variable, continuous but delayed	Very rugged and reliable. Sealable. No moving parts. Lifetime greater than 10 years.
Apparent wind	v^3	None	Indirect	Body, 5-20 W (low)	(ac or dc) Variable (speed) continuous	Fragile, protective housing needed. Exposed components. Moving parts.
Radioisotope thermoelectric	None	None	None	Body 2 W (10 ohms)	(dc) Steady	Very rugged. Highly reliable. No moving parts. Sealable. 20-year life.
Solar	None	None	None	Body	(dc) Variable (weather orientation, diurnal variation)	Transparent protective cover needed. Reliable. No moving parts. Sealable. 15-20 year cell life.

TABLE 6.1

ASSESSMENT SUMMARY

8	9	10	11	12	13	14
Main Failure Mode	Technology	Energy Source	Energy Storage Requirements	Installation and Package	Temperature in °C	Relative Cost of Device
Wear, metal fatigue	Well developed in other products. Engineering needed.	Vibration	Rechargeable battery	Add-on device, completely encased	Probably -50 to 50 (development needed)	$300 (?)
Crystal fracture	Highly developed. Engineering and specific designs needed.			Add-on, completely encased.	-40 to 200	$200
Crystal fracture, wear		Vibration	Rechargeable battery	Modification to suspension needed.	-40 to 200	$200 plus cost of modifications
Unknown	New material. No comparable application known.			Add-on. Completely encased.	-40 to 40. Permanent damage above 40.	--
High-resistance or open-circuits junctions.	Highly developed. Manufactured components exist.	Bearing heat	Rechargeable battery	Some bearing adapter modification required.	T must be maintained. Ambient temp. -40 to 200 possible.	$500 plus cost of modifications.
Damage. Wear. Turbine blockage by objects and snow/ice.	Developing. Engineering needed. Components exist.	Forward movement of train.	Rechargeable battery	Add-on device. Must be exposed to wind stream.	-40 to 50 Ice accumulation could be a problem.	$300
	Highly developed. Manufactured product exists.	Heat from plutonium.	None	Add-on anywhere. Completely enclosed.	-50 to 50	$150 plus cost of plutonium, estimated at $10,000 to $25,000.
Damage to panel. Contact failure.	Highly developed, but improvements continue to be made. Manufactured product exists.	Sunlight.	Large-capacity rechargeable battery.	Add-on, car side or top mounting.	-40 to 100	$500-$1,000. Potentially low.

(2) The energy conversion technologies which showed promise in a cursory study, and which were subsequently investigated in detail, are: (i) the linear electrodynamic generator, piezoelectric ceramics and piezoelectric polymers driven by vibration, (ii) wind-turbine generators driven by the apparent wind of motion, (iii) thermopiles operating on bearing heat, (iv) radioisotope-thermoelectric generators, and (v) photovoltaic cells employing sunlight.

(3) The only device which meets or exceeds all of the guideline requirements is the radioisotope-thermoelectric generator (RTG). Furthermore, the device has a twenty-year life, does not require energy storage, and is the only technique for which a suitable manufactured product currently exists. However, it is probably the least "socially" acceptable system because it employs a radioactive substance, plutonium. It could also be very expensive, the cost depending on the price of the government-regulated plutonium. RTGs could be of interest as power sources for end-of-train units.

(4) An inherent problem with any system driven by track-induced vibration is that as the track condition improves, the output power decreases, and the periods of adequate delivery will become shorter and less frequent. If the trend is toward improvement of tracks generally in order to reduce fuel consumption, then a vibration-driven device which is adequate now would be expected to become less effective in the future. Newer types of trucks with lower vibration will have the same effect.

(5) A truck-mounted power source is less desirable than a body-mounted device for delivering power to electronic systems on the body because of the need for cabling, flexible, protective conduit, and rugged, environment-proof connectors between the truck and the body.

(6) The linear electrodynamic generator is a moderately rugged, mechanically simple device capable of meeting the guideline power requirements when mounted on a truck. Body mounted, its power output would be lower by a factor of 100. The relevant electrical and mechanical technologies are highly developed; however, a device for this specific railway application would have to be designed and engineered. The major disadvantage

of this technique would appear to be its dependence on track condition, as described in item (4) above. Energy storage is necessary because power delivery will be erratic. The most likely failure mode would be failure of the spring-mass system due to metal fatigue. Good design could provide ruggedness and protection against damage from high-g impacts. It can be completely enclosed and packaged as a simple add-on unit. However, the linear, electrodynamic generator should not be developed further because of the limitations indicated in item (4) above.

(7) Vibration-driven devices using piezoelectric ceramics would be based on a highly developed transducer technology. Experience with piezoelectric accelerometers suggests that power sources could be rugged, reliable and highly environment resistant, as well as structurally simple. The problems with piezoelectric-ceramic generators are that in the accelerometer mode of operation they can deliver only sub-milliwatt power, while in the compression mode 1 watt can be delivered, but only with voltages of the order of 10^4 V from source impedances of tens of megohms. Compression-mode systems would require integration of the device into the suspension system. Fracture of the relatively large ceramic elements is a most likely failure possibility. Devices based on piezoelectric ceramics are not considered practical.

Piezoelectric PVF_2 polymer, employed in the form of bimorphs in layers, does not appear to be capable of delivering adequate power in a practical device. Being a polymeric material, the mechanical properties of PVF_2 would be expected to change significantly over the range of temperatures encountered in the railway environment. Commercial devices are made using PVF_2, but not of the size and for the type of environment being considered here. Lifetimes are also uncertain as polymers suffer mechanical relaxation under prolonged stress and the piezoelectric effect, which is induced artifically, can weaken.

Piezoelectric devices are dependent on track condition, as described in item (4) above.

(8) Wind-driven generators powered by the apparent wind of the moving train are capable of producing more than adequate power at 40 km/h (25 mph). The technology is well developed for the various components needed; however, special designs must be engineered for the freight-car environment.

Propellers, or turbines, and their mechanical mounts are the most susceptible to damage of any of the components considered in this study. The wind-powered system, being more complicated than the others, is expected to be less reliable. The main failure problems foreseen are jamming of the turbine by foreign objects or snow and ice, and blockage of the air stream by snow, leaves, paper or clothing. On the positive side, a wind-powered generator would generate a more than adequate level of power and deliver the power continuously as long as train speed is maintained. Power generation is independent of track condition and the device would be mounted on the body (see item (5) above).

For wind power to be viable on a freight car, the problem of how to protect the turbine system, yet allow free air flow, has to be solved. The development of an innovative turbine/housing scheme could make wind power a practical solution.

(9) The conversion of bearing heat to electricity by means of thermopiles is attractive. A thermoelectric system could, in principle, produce the required power using highly reliable semiconductor elements and no moving parts. A highly developed technology supported by a well-established industry manufactures the necessary components. Applications in other harsh environments have been very successful because of the ruggedness and reliability that can be achieved. A thermoelectric system can be sealed against environmental factors and can provide a very long (twenty-year) service life. Set against these attractive features are: (i) the need to have a large area of contact, approximately 250 cm^2 (36 $in.^2$), because of the relatively small temperature difference available, (ii) a delay of 20 to 60 minutes from the start of train motion before useful power is delivered, and (iii) the fact that this system must be mounted on the truck, or trucks, of the car, with some modification to the bearing adapter. The thermopile source with a rechargeable battery is considered a very attractive candidate for a lower-power, on-board power supply. For powers in the 10 to 100 mW range, the contact area would not be a practical problem.

(10) Solar energy is capable of supplying more than adequate total energy over a year with a solar panel collecting area of about 0.5 m^2. This estimate takes into account accumulation of dirt and

periods of almost complete shading of the panels which will occur in the rail environment. Because of seasonal, monthly and daily variations in the available solar energy, storage requirements are greater than with other systems. A rechargeable cell with sufficient capacity to maintain the electrical system for at least 15 days would be advisable. On the other hand, the solar panel will recharge the battery any time there is sufficient solar energy, regardless of whether the car is moving or not, full or empty. A major problem with the solar-powered system is the mounting and protection of the solar panels, especially on hopper and flat cars, the latter requiring a structure which could be vulnerable to damage. Suitable panels are available, and have been used on cabooses by Southern Railroad in the United States. Railway experience in a number of wayside applications of solar power is that the systems are rugged and reliable. If adequate protection against damage could be assured on freight cars, solar panels would be a very attractive on-board source.

7.1 Summary of Conclusions

(1) The only electric generating technique encountered which satisfies all of the guideline requirements is the radioisotope-thermoelectric generator (RTG). However, there could be an acceptability problem and the cost could be high.

(2) Vibration-driven generators have the inherent problem that average power output decreases and power delivery becomes more intermittent as track condition and truck designs improve.

(3) Of the vibration-driven schemes, the linear-electrodynamic generator concept has the greatest potential for a practical system, provided the vibrational energy is adequate, a situation most likely to be true only on the trucks of the freight car and on rough track.

(4) Wind-powered generators offer several attractive features which include body-mounting and power levels exceeding the guideline requirement. A viable system will be possible only if a housing can be devised for the turbine to protect it from physical abuse, snow, foreign objects, etc., while permitting an adequate air flow.

(5) Thermoelectric generation from bearing heat is probably the most reliable and rugged technique studied, except for the RTG which also uses the thermoelectric effect. Because of the low temperature differentials available, an excessively large hot-contact area is necessary to achieve the guideline power levels. Therefore, this technique would be better suited to supplying power of the order of 100 mW. Power delivery is continuous after an initial delay of 20 to 60 minutes. A rechargeable battery is needed to supply power during this warm-up period.

(6) Piezoelectric vibration-driven devices are not considered practical for this application.

(7) Solar energy is a very attractive solution worthy of further consideration. The special needs of the freight-car application are protection of the solar-cell panel and the relatively long (15 to 30 days) storage capacity to reliably provide year-round operation.

8. RECOMMENDATIONS

(1) The radioisotope-thermoelectric generator (RTG) should be considered for specialized applications such as ETUs. Since access, acceptability and cost may make plutonium impractical, the use of other radioisotope heat sources of a less toxic nature should be explored.

(2) Solar power shows sufficient promise as an on-board power source that it should be given further consideration. Current technology is capable of meeting the power requirements of a car. However, because this technology continues to show improvements with respect to efficiencies and cost, the future promises compact, low-cost, on-board systems. Therefore, commercially available solar panels designed for harsh environments should be field-tested to establish whether they are sufficiently rugged for this application or, if not, where improvements are necessary.

(3) The various types of wind turbines and innovative ideas for a protective housing should be explored in greater depth than was possible in this project.

(4) Power sources driven by vibrational energy should not be developed for railway applications because ongoing and future improvements to tracks and trucks will progressively undermine their effectiveness.

(5) Thermoelectric generators should be considered where power levels of 10 to 100 mW are needed, bearing in mind the need for a rechargeable battery to supply power during the warm-up time and the inconveniences of a truck-mounted device.

(6) Battery technology appropriate for on-board energy storage needs to be investigated, with particular attention to usable life, low-temperature operation, and ability to withstand prolonged vibration.

REFERENCES

Aitken, G.J.M. (1982), Review of Signal and Power Transmission Technology for Freight Trains, Canadian Institute of Guided Ground Transport, Queen's University, Kingston, Ontario, Canada, Report No. 84-4.

Allen, G.E., et al. (1979), Prevention of Roller Bearing-Initiated Burnoffs in Railroad Freight Car Journals, U.S. Department of Transportation, Federal Railroad Administration, Report No. FRA/ORD-78/16, January 1979.

Angrist, S.W. (1982), Direct Energy Conversion, (Boston, Mass.: Allyn and Bacon).

Armstrong, J.H. (1979), "Railroads Plug Into Solar Power," Railway Age, September 24, 1979, pp. 16-20.

Auer, P.L. (1979), Advances in Energy Systems and Technology, Vol. 1, Academic Press.

Barthelemy, R.R., and Massie, L.D. (1983), "Future Military Space Power Systems and Technology," 18th Intersociety Energy Conversion Engineering Conference, August 21-26, Orlando, Florida, pp. 932-940.

Bennett, G.L., et al. (1983), "U.S. Radioisotope Thermoelectric Generator Space Operating Experience (June 1961-December 1982)," 18th Intersociety Energy Conversion Engineering Conference, August 21-26, Orlando, Florida, pp. 1044-1055.

Benson, D.K., and Jayden, T.S. (1980), "Thermoelectric Energy Conversion: Economical Electric Power from Low Grade Heat," 3rd International Conference on Thermoelectric Energy Conversion, March 12-14, Arlington, Texas, pp. 27-56.

Bernsteen, S.A., et al (1980), "The Interpretation of Train Rolling Resistance from Fundamental Mechanics," Joint IEEE-ASME Railway Conference, Montreal, Quebec, pp. 41-52.

Dichler, A. (1981), "Power from the Sun," Railway Gazette International, December 1981, pp. 1031-1033.

G.A. Technologies, "Radioisotope Thermoelectric Generator (RTG)," product data sheet, G.A. Technologies, San Diego, California, 92138.

Greatbatch, W. (1984), "Pacemaker Power Sources," IEEE Engineering in Medicine and Biology Magazine, June 1984, pp. 15-19.

Iles, P.A. (1982), "Current Developments in Silicon Space Cells," 17th Intersociety Energy Conversion Engineering Conference, August 8-12, Los Angeles, California, pp. 1624-1626.

IRJ (1983), "Railways Plug Into the Power of the Sun," International Railway Gazette, September 1983, pp. 58-62.

Kamath, G.S. (1982), "Status of GaAs Solar Cells for Space Power Applications," 17th Intersociety Energy Conversion Engineering Conference, August 8-12, Los Angeles, California, pp. 1635-1639.

Kazmerski, L.L. (1981), "Advances in Photovoltaics R and D: An Overview," 16th Intersociety Energy Conversion Engineering Conference, August 9-14, Atlanta, Georgia, pp. 1637-1641.

Kentfield, J.A.C. (1983), "The Performance of Simple Horizontal-Axis Wind-Turbines for Direct Drive of Water Pumps, "18th Intersociety Energy Conversion Engineering Conference, August 21-26, Orlando, Florida, pp. 1360-1366.

Kettani, M.A. (1970), Direct Energy Conversion, (Reading, Mass.: Addison-Wesley).

Love, R.B., and Hussain, S.M.A. (1978), Suspension Dynamics - Vol. II, Association of American Railroads, Report No. R-350, December 1978.

Marcus, M.A. (1982), "Ferroelectric Polymers and Their Applications," Ferroelectrics, Vol. 40, pp. 29-41.

Merrigan, J.A. (1982), Sunlight to Electricity, 2nd ed., (Cambridge, Mass.: MIT Press).

Mitchell, R.L. (1984), "Overview of the Electrofluid Dynamic Wind-Driven Generator," J. Solar Energy Engineering, Vol. 106, pp. 307-311.

Mullin, J.P., et al. (1982), "The NASA Program in Space Energy Conversion Research and Technology," 17th Intersociety Energy Conversion Engineering Conference, August 8-12, Los Angeles, California, pp. 2150-2162.

Nance, P. (1980), G-Sensing Derailment Detector, U.S. Dept of Transportation, Federal Railroad Administration, Report No. FRA/ORD-80/75, October 1980.

Olsen, R.B. (1984), "Pyroelectric Conversion in Space," 19th Intersociety Energy Conversion Engineering Conference Proceedings, pp. 224-8.

Peacock, T.V., and Snider, H.H. (1980). Railroad Car Roller Bearing Temperature Measurement and Analysis, U.S. Dept of Transportation, Federal Railroad Administration, Report No. FRA/ORD-80/43, April 1980.

Prenis, J. (1975), Energy Book No. 1, (Philadelphia, Penn.: Running Press).

Pulfrey, D.L. (1978), Photovoltaic Power Generation, (New York, N.Y.: Van Nostrand Reinhold).

Raghunathan, S., and Tan, C.P. (1984), "Performance Prediction of the Wells Self-Rectifying Air Turbine," 19th Intersociety Energy Conversion Engineering Conference, pp. 1-6.

Rosell, F.E., and Vogt, J.F. (1978), "Recent Terrestrial and Undersea Applications of Radioisotope Thermoelectric Generators (RTGs)," 13th Intersociety Energy Conversion Engineering Conference, August 20-25, San Diego, California, pp. 1969-1977.

Schmidt, V.H., et al. (1983), "PVF_2 Bimorphs as Active Elements in Wind Generators," Ferroelectrics, Vol. 51, pp. 105-110.

Scott-Monck, J. (1982), "Space Solar Cell Technology Development," 17th Intersociety Energy Conversion Engineering Conference, August 8-12, Los Angeles, California, pp. 1619-1623.

Sheskin, T.J., et al. (1982), "Performance Degradation and Cleaning of Photovoltaic Arrays," 17th Intersociety Energy Conversion Engineering Conference, August 8-12, Los Angeles, California, pp. 1504-1510.

Solarex (1981), "Solar Electric Panels for Railroad Applications," product data sheets 8000-1 9/81, Solarex Corporation, 1335 Piccard Drive, Rockville, Maryland 20850. Also data sheets 6027-1 2/83 and 6024/2 6/83.

Sorensen, H.A. (1983), Energy Conversion Systems, (New York, N.Y.: John Wiley).

Stapfer, G. (1980), "Advanced Thermoelectric Material Development at JPL," 15th Intersociety Energy Conversion Engineering Conference, August 18-22, Seatle, Washington, pp. 1595-1599.

Symon, K.R. (1953), Mechanics, (Reading, Mass.: Addison-Wesley).

Tanaka, T. (1982), "Piezoelectric Devices in Japan," Ferroelectrics, Vol. 40, pp. 167-187.

Trumble, T.M. (1982), "Space Applications of Gallium-Arsenide Solar Cells," 17th Intersociety Energy Conversion Engineering Conference, August 8-12, Los Angeles, California, pp. 1631-1634.

Vernitron (1985), "Piezoelectric Technology Data for Designers," Vernitron Piezoelectric Division, 232 Forbes Road, Bedford, Ohio 44146.

APPENDIX A

AVAILABLE POWER SOURCES

A.1 INTRODUCTION

The purpose of this Appendix is to identify the possible sources of power on a car and to estimate the likely level of the available power. The useful sources identified are heat from bearings, truck and car body motion in the form of vibration, the apparent wind due to the forward movement of the car, radioisotope heat, and solar power. Because the objective of this section is to establish the level of power that would be reliably available in normal operation, attention has been directed to the conditions that will indicate lower bounds. For discussion purposes a speed of 25 mph (40 km/h) has been employed as a typical freight car speed.

A.2 ROLLER BEARING HEAT

Rolling resistance due to roller bearing friction is given by [Bernsteen et al (1980)]:

$$R_B = 402\ V^{1/2}\ r^{-3/2}\ (W/n)^{-2/3} \qquad (A.1)$$

where: R is in watt-hours/ton-km (Wh/t-km)

v is the forward speed in km/h

r is the radius of the wheels in cm

W is the weight of the car less the wheels and axles in tons

n is the number of axles per car.

The formula applies to cars of the order of 10^2 tons in weight and at speeds greater than 0.8 km/h. Note that the unit "Wh/t-km" can be interpreted as watts per unit speed for each ton of car (watt/(ton-km)). R_B is plotted in Figure A.1 for r = 46 cm (18 in.). Note that the commonly used term "watt-hours/ton-mile" is related to the metric equivalent by Wh/t-mi = 1.6 Wh/t-km.

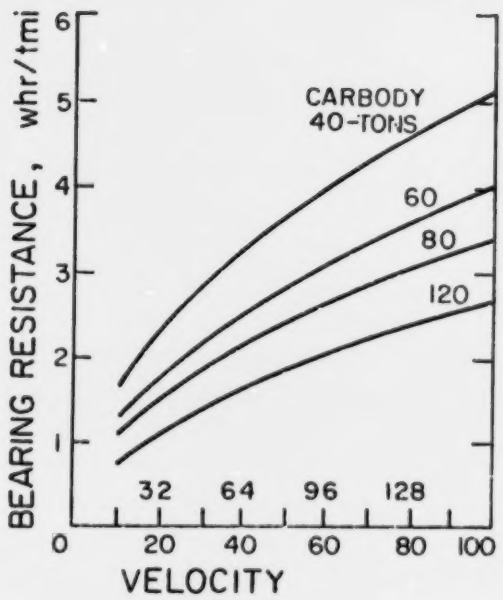


Figure A.1 Bearing resistance for cars of different weights. The wheel radius is 46 cm (18 in.). Upper velocity scale is in km/h, lower in mph. [Bernsteen et al (1980)]

The power consumed in bearing friction is:

$$P_B = R_B W v \qquad (A.2)$$

which, when combined with equation (A.1), gives:

$$P_B = 402\, r^{-3/2}\, n^{2/3}\, W^{1/3}\, v^{3/2} \qquad (A.3)$$

At 40 km/h, a 40-ton car would consume 355 watts per bearing as frictional resistance. This power is, of course, dissipated as heat.

The efficiency with which heat energy can be extracted from a source depends on the temperature difference that can exist between the source and sink. The theoretical maximum efficiency is:

$$\eta = \frac{T_h - T_c}{T_h}$$

where: T_h is the hot temperature of the source in absolute degrees

T_c is the cold temperature of the sink in absolute degrees.

Measured bearing temperature as a function of time for normal roller bearing operation is shown in Figure A.2 for an unloaded car and in Figure A.3 for a loaded car [Peacock and Snider (1980)]. The temperature was measured on the outer casing of the bearing. It is clear from the figures that it can take up to an hour to reach the equilibrium or steady temperature and that the steady temperature depends on train speed. Comparison of Figures A.2 and A.3 shows how car weight affects the temperature. For these measurements the unloaded car weighed 32 tons while the loaded car weighed 116 tons.

The results of a series of investigations are shown in Table A.1 which suggests that at 48 km/h (30 mph) the difference in temperature available for thermoelectric generation would be only 19.5°C (35°F) with the unloaded car while for a loaded car it would be 36°C (65°F). Of course, at higher speeds the temperature difference is higher, reaching 58°C (105°F) for a loaded car at 80 km/h (50 mph). For

TABLE A.1

SUMMARY OF BEARING TEMPERATURE DATA

Test	Car Condition	Train Speed (km/h)	Ambient Temperature (°C)	Bearing Temperature (°C)	Difference Temperature (°C)
Aug./76	loaded	72	32	81	49
Aug./76	loaded	72	32	79	47
Dec./77	unloaded	48	4.5	24	19.5
Dec./77	unloaded	80	4.5	34	52.5
July/78	loaded	48	35	71	36
July/78	loaded	80	35	93	58

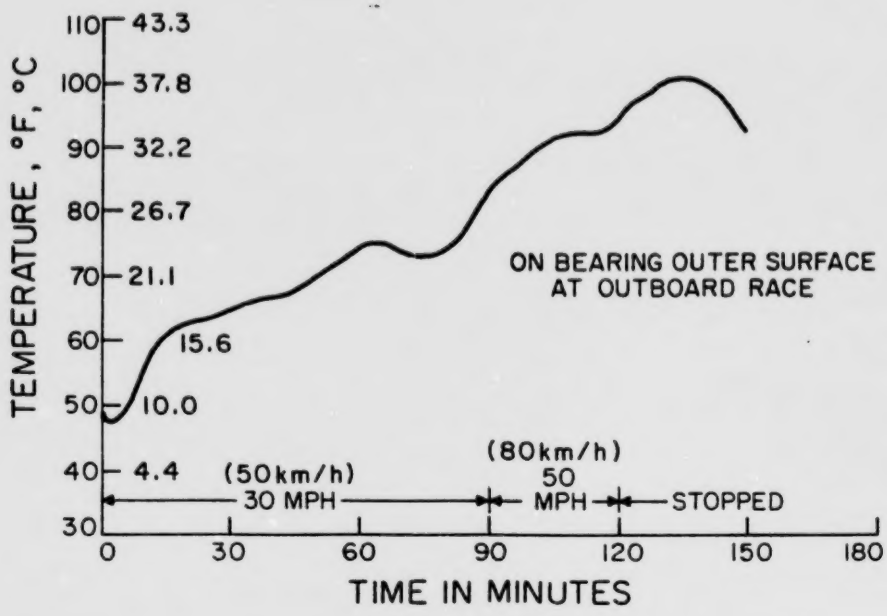


Figure A.2 Temperature of a normal freight-car roller bearing with the car unloaded (32 tons) [Peacock and Snider (1980)]

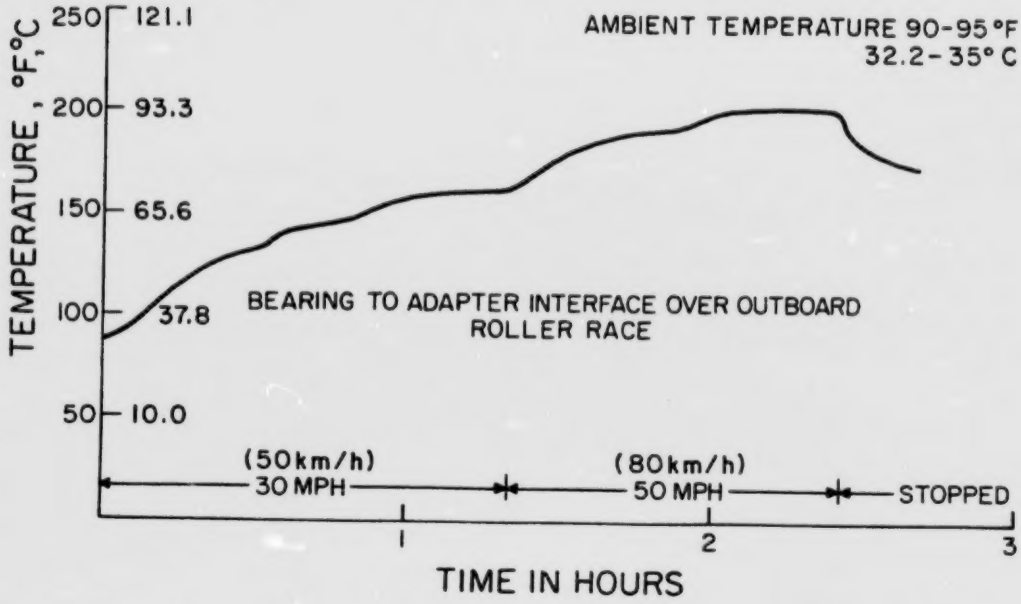


Figure A.3 Temperature of a normal freight-car roller bearing with the car loaded (116 tons) [Peacock and Snider (1980)]

purposes of analysis in Appendix E, a temperature difference of 30°C has been used. The maximum possible conversion efficiency, η, will be 6.4 per cent with an unloaded car at 48 km/h and 18.5 per cent with a loaded car going 80 km/h.

One practical problem with a heat source generator is the time required after a cold start to raise the temperature of the bearings to the point where practical thermoelectric conversion could take place. This delay could be as much as 20 to 60 minutes, depending on the load, speed, ambient conditions and characteristics of the thermoelectric device employed.

A.3 ENERGY DISSIPATED IN THE SUSPENSION

Motion in the suspension system of a freight car is caused by the wheel/rail interaction and is a function of the vehicle design, load, track characteristics and speed [Bernsteen et al (1980)]. The track characteristics, which determine the driving forces and displacements applied to the wheels, can be described by four principal functions:

- the vertical undulations of the surface which cause bounce and pitch
- the crosslevel tilt due to alternate vertical displacements of the left and right rails which causes a rolling motion
- alignment variations or "snaking" of the track
- gauge variations.

By far the most important effect is surface undulations with the effects of crosslevel tilt being much less. The alignment and gauge variations do not contribute significantly to motion in the suspension. An ideal track would have both rails on a horizontal plane with no displacements from straight parallel lines. The degree to which real rails depart from this ideal is characterized by the FRA track classification system in which the numbers 1 to 6 represent very poor to very good tracks. An example of suspension energy dissipation for a class 4 track is shown in Figure A-4. These results were obtained from a computer simulation [Bernsteen et al (1980)] but are representative of

what is observed in practice. Welded rail causes noticeably less dissipation than jointed rail because the small impulses given to the wheels at the joints have been eliminated. The results in Figure A-4 can be applied to other classes of track by means of the conversion factors in Table A.2.

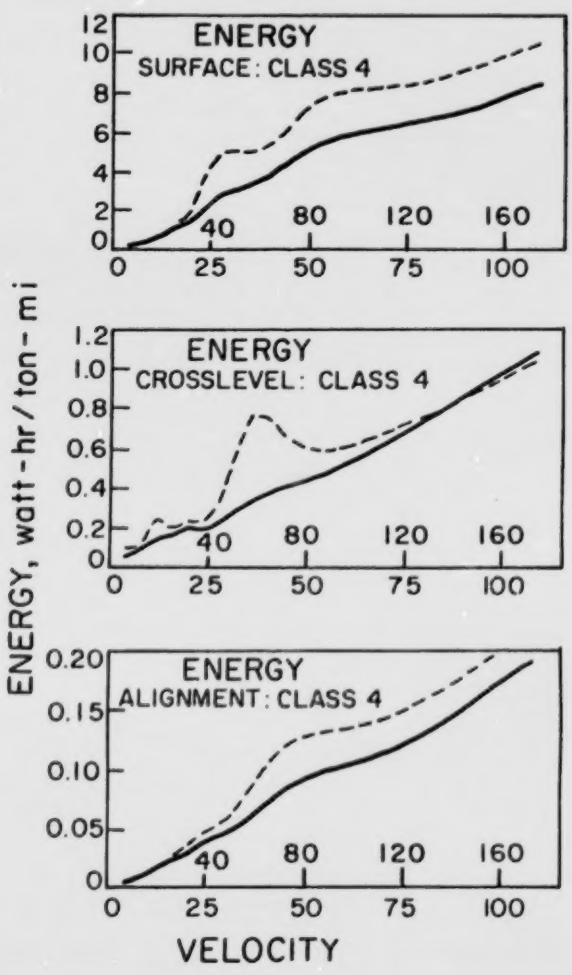


Figure A.4 Energy dissipation in the suspension on a class 4 track. Dashed lines represent jointed rail, solid lines are for welded rail. Upper velocity scale is in km/h, lower in mph. [Bernsteen (1980)]

TABLE A.2

FACTORS FOR CONVERTING CLASS 4 RESULTS TO OTHER CLASSES

	Surface		Cross-Level		Alignment	
Class	Power	RMS	Power	RMS	Power	RMS
6	0.0625	0.250	0.250	0.500	0.111	0.333
5	0.391	0.625	0.640	0.800	0.250	0.500
4	1.000	1.000	1.000	1.000	1.000	1.000
3	1.266	1.125	1.960	1.400	1.361	1.167
2	3.357	1.833	2.941	1.715	6.618	2.572
1	4.000	2.000	6.618	2.572	18.38	4.287

Obviously, the worse the track the more power there will be available in the suspension. Consequently, a general-purpose electric power generator should be designed for adequate operation on class 6 tracks. From Figure A.4(a) and Table A.2 the resistance due to the dissipation in the suspension of a car travelling 40 km/hr (25 mph) on class 6 welded rail would be R_s = 0.097 Wh/t-km (0.156 Wh/t-mi). Thus, the power dissipated by a 40-ton car would be 156 watts, and dissipation on one side of one truck would be about 40 watts. Under the same conditions the dissipation on one side of a truck on class 4 track would be 625 watts. The dissipation caused by crosslevel tilt and alignment variations on class 6 track are 3 and 300 times lower, respectively, than the contribution due to surface undulations. On the other hand, the average speed of a train can be higher on the better track. Therefore, if the train speed is 80 km/h (50 mph) on our class 6 track the dissipation will 160 watts instead of 40 watts.

It is clear from the factors in Table A.1 that the power being consumed in the suspension, and which might be tapped to drive a generator, is very sensitive to the track condition. Furthermore, since R_s is almost linearly dependent on speed, v, in the case of welded rail, the power dissipated is proportional to v^2, while it is directly proportional to car weight.

An important characteristic of the vibrational energy dissipated in the suspension is the local accelerations caused in the trucks and car body. On a class 4 track the dissipation in the suspension of a 40-ton car travelling 40 km/h is 2500 watts, split equally between the two trucks. A calculation of the vertical acceleration corresponding to this power, the mass, spring constants and damping of a typical suspension system [Bernsteen et al (1980)] suggests rms values of about 1.5 g on the side frames at resonance. This figure would be an average along the track. A precise figure is difficult to find because the accelerations depend on the amount of damping and other parameters of the suspension. Also, a linear damping function has been used instead of a constant damping force.

Examples described in reference [Love and Hussain (1978)] give vertical wheelset accelerations of the order of 5 to 18 g for 1 inch depressed joints at speeds in the 50-60 mph range. However, since the rolling resistance factors were determined from spectral density functions of track profiles, the lower values derived from them represent average or typical expected values along the tracks. Reference [Love and Hussain (1978)] gives accelerations of the car body and bolster as well as the wheelset-sideframes. As a general rule the vertical accelerations in the bolster were about five times greater than in the wheelset, and the vertical acceleration of the body about ten times less than in the wheelset. On class 6 track the acceleration values would be four times less than for class 4 track.

Measurements made on a "smooth" section of DM and IR Railway track using accelerometers mounted on a truck gave an rms acceleration of opproximately 8 with a strong, sharp spectral component at a frequency less than 5 Hz and a broader spectral peak in the vicinity of 50 Hz [Nance (1980)]. The wheelset mass and track stiffness have a resonance of this order, with the car mass and springs resonating at about 2 Hz. Unfortunately, the classification and condition of the section of track are not known. Nevertheless, these figures indicate that our estimate of 1.5 is of the correct order and may, in fact, be a conservative underestimate. The measured spectral density is shown in Figure A.5.

The energy dissipated in the truck suspension must ultimately be converted to heat in the springs and at the wear faces of the snubbers. Because of the large mass of heat-conducting metal and the

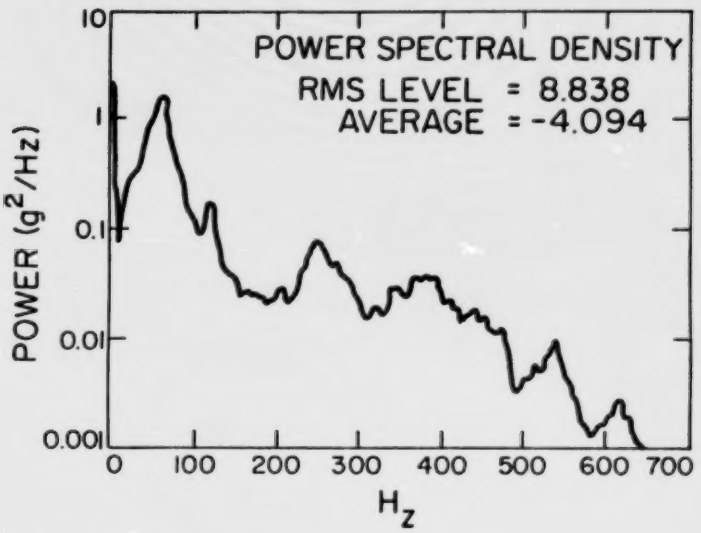


Figure A.5 Power spectral density of truck acceleration [Nance (1980)]

relatively free circulation of air around the suspension elements when the train is in motion, the components of the suspension system do not reach temperatures sufficiently high to make the extraction of energy by thermoelectric conversion practical. The available energy must be tapped by mechanical coupling to the moving suspension elements or by inducing vibration in an auxiliary element.

A.4 APPARENT WIND

The forward motion of the freight car through the air creates an apparent wind blowing in the opposite sense to the car motion. In principle energy can be extracted from this wind by conventional propellers and turbines. At this point it is of interest to establish the amount of power available. Because the air itself may be in motion because of a natural wind, it is necessary to define the apparent wind more precisely as having a velocity.

$$\vec{v}_a = \vec{v}_n - \vec{v}_c$$

where: $\vec{v}_n$ is the velocity of the natural wind

$\vec{v}_c$ is the car velocity.

If a conventional propeller were employed, only the component parallel to the car would be of interest. Let the reference direction for the wind be the direction of motion of the car, and the angle that the natural wind makes with the car be 0, as shown in Figure A.6, then the speed of the apparent wind is:

$$v_a = v_n \cos 0 + v_c \qquad (A.4)$$

where v_a, v_n and v_c are the magnitudes, or speeds, of the respective velocities. From Appendix D, the theoretical maximum power that can be extracted from this wind under steady-state, steady-flow conditions is:

$$p_w = (8/27)\ \rho\ A\ v_a^3 \qquad (A.5)$$

where: ρ is the density of the air

A is the cross-sectional area of the wind stream which is intercepted.

With an air density of 1 kg/m^3, v_a = 40 km/h (25 mph) and A = 1 square metre, the power generated would be 406 watts/m^2. At 5 mph the output would drop to 3.2 watts/m^2, which illustrates the very strong dependence of output power on velocity. A realistic cross-sectional area on a freight car is probably 0.1 m^2 or less, in which case the maximum power figures given above would be reduced by a factor of 10.

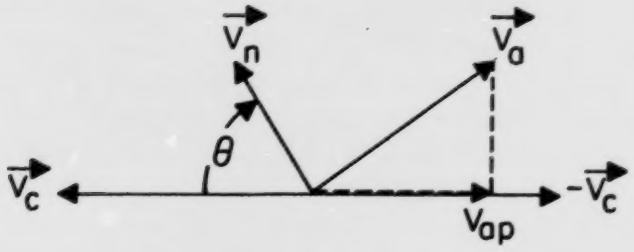


Figure A.6 Vector diagram of wind velocities. The resultant apparent wind parallel to the direction of motion is v_{ap}

One problem area with the wind-driven power generation can be seen in equation (A.4). If θ is between 90° and -90°, the natural wind will tend to cancel the wind created by train motion. With the delivered power being proportional to v_a^3, any reduction in v_a will have serious consequences. It is quite conceivable that there would be times when a strong tail wind on a long straight section of track could mean inadequate power generation for long intervals. One solution that should be examined is turbines which have a non-directional response to the wind.

A.5 OTHER

The possibility of using the draw-bar motion has been considered but found to be impractical. Large forces are available both longitudinally and laterally, but work can be done only if the forces act through a displacement. Energy produced by longitudinal forces would be impulsive in nature and would occur only if there were longitudinal oscillations of the car, an undesirable condition. Both longitudinal and lateral motion of the draw-bar can often be non-existent. Lateral forces are generatd by the hunting and rolling of the car, effects which depend on track characteristics. In both cases the frequency of the oscillations will be low, less than 1 Hz, which makes efficient extraction of the energy difficult.

Heat from brakes is not considered a viable possibility, although quite high differential temperatures can occur. The problem is that brake heat is very much a function of the frequency and duration of application and as such would vary considerably from one route to another and with the make-up of the train consist.

The rotating journal end cap presents a readily-accessible source of high rotational energy. Without violating the requirement that no mechanical connection be made to wheels and axles (Section 3), a small portion of the available energy could be extracted by means of electromagnetic coupling. Conceptually, a generator would consists of several strong magnets imbedded in the periphery of the end cap so that they sweep past coils mounted in a casing around the bearing housing. This is essentially the same idea as the magneto spark generator used in small gasoline engines.

Sources available, but not resulting from the car motion, are:

- radioisotope heat sources which can produce tens of watts of thermal energy at high differential temperatures with only a few grams of plutonium
- solar energy which can deliver 4,000 Wh/m^2 per day on average in southern Canada.

The solar energy flux can be hundreds of $watts/m^2$.

APPENDIX B

LINEAR ELECTRODYNAMIC CONVERTERS

B.1 INTRODUCTION

An electrodynamic converter changes mechanical energy to electrical by mo ing a coil of wire through a magnetic field. The term linear indicates that the motion is along a line, in contrast to the rotary motion of a conventional generator or alternator. The principle is used in the magnetic phonograph pickup, and in velocity measuring devices. A configuration which could be employed as a mechanical-to-electrical energy converter is illustrated in Figure B.1 [Nance (1980)]. The essential components are a coil, a magnet, flux concentrators, a spring and a sealed container. The flux concentrator is supported by the spring in a manner which allows it to freely move parallel to the axis of the fixed coil. The dynamic system consists of the mass of the flux concentrator and the spring, which together form a mechanical resonator. Any acceleration of the container creates a proportionate force on the mass and causes a displacement. Time-varying oscillatory accelerations produce an oscillatory motion of the magnetic field, which then generates a voltage across the coil proportional to the field's instantaneous velocity relative to the coil. When a resistive load is connected to the coil a current flows, causing a damping force in the resonator. The power delivered to the external load is seen by the mechanical system as the power dissipated in damping. Thus, the power consumed by a damped mechanical resonator represents the maximum power deliverable by the electrodynamic converter.

B.2 MECHANICAL DYNAMICS

The damped mechanical resonator shown in Figure B.2 is described by the differential equation [Symon (1957)]:.

$$m \ddot{x} + b \dot{x} + k x = F(t) \qquad (B.1)$$

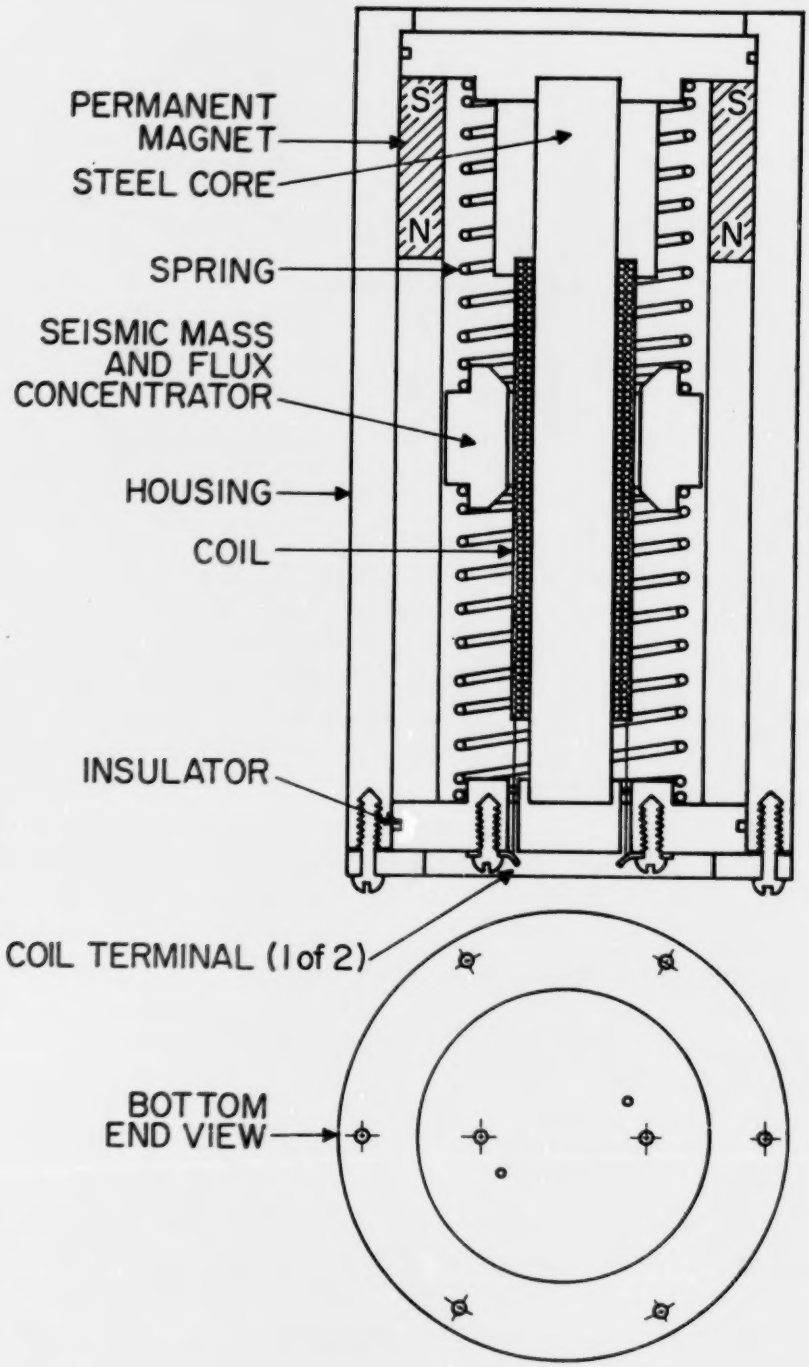


Figure B.1 Cross-section and end view of a linear electrodynamic energy converter

where: x, $\dot{x}$ and $\ddot{x}$ are the displacement, velocity and acceleration of the mass m

b is the damping factor

k is the spring constant.

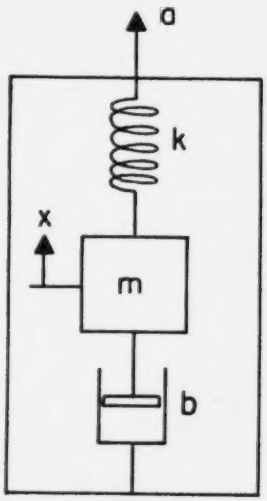


Figure B.2 Model of the mechanical resonator for analysis

The driving force, F(t), will be assumed to be due to the acceleration, a(t), of the system. A cosinusoidal acceleration with a peak value of a_m is assumed; therefore:

$$F(t) = m\, a_m \cos \omega t \qquad (B.2)$$

where the angular frequency is $\omega = 2\pi f$, f being the frequency in Hertz.

The steady-state solutions to equation (B.1) for a driving force (B.2) are:

$$x = p(\omega)\, a_m \cos (\omega t - \theta) \qquad (B.3)$$

$$\dot{x} = p(\omega)\, a_m \sin (\omega t - \theta) \qquad (B.4)$$

where: $p(\omega) = [(\omega_o^2 - \omega^2)^{1/2} + \omega^2 b^2/m^2]^{1/2}$ (B.5)

$\theta = \tan^{-1} [\omega b/m(\omega_o^2 - \omega^2)]$ (B.6)

$\omega_o = (k/m)^{1/2}$, the natural resonance frequency.

The average power delivered to the resonator is:

$$P_{av} = \frac{1}{2} \int_o^T F(t)\ \dot{x}\ dt \qquad (B.7)$$

T being the period of oscillation ($T = 2\pi/\omega$).

Substitution of equations (B.2) and (B.4) in (B.7) yields:

$$P_{av} = \frac{1}{2}\ p^2(\omega)\ a_m^2\ \omega^2\ b\ . \qquad (B.8)$$

For the special case of the driving function having an angular frequency equal to the resonance frequency, that is $\omega = \omega_o$, $p(\omega) = m\omega b$, and

$$P_{avo} = a^2\ m^2/2b \qquad (B.9)$$

Critical damping is the condition where the damping is just sufficient to prevent the natural response of the system from oscillating. This occurs when $b = 2\ m\ \omega_o = 2\sqrt{km}$. The average power delivered to a critically damped system is:

$$P_{av} = a_m^2\ m\ \omega_o \left[\frac{\omega^2}{(\omega_o^2 + \omega^2)^2}\right] \qquad (B.10)$$

The quantity $p(\omega)$ indicates that the response of the system decreases as $|\omega_o - \omega|$ increases. The bandwith between frequencies at which the response is down by a factor of 2 is given by:

$$\frac{\Delta\omega}{\omega_o} = \frac{1}{Q} = \frac{\omega_o m}{b} = \frac{k}{\omega_o b} \qquad (B.11)$$

where Q is called the quality factor of the resonant system. The greater the damping, the broader will be the frequency response.

B.3 ELECTRODYNAMICS

If a magnet moving at a velocity, v, produces, by means of the flux concentractors, a radially directed flux density, B, which cuts N turns of a coil of radius r, the emf in volts between the coil terminals is:

$$E = (2\pi r)\ N\ B\ v \qquad (B.12)$$

when: B is in webers/m^2

v is in m/sec

r is in metres.

Let ℓ be the length of the total coil, ℓ_g the length of the gap containing the magnetic flux and N_t the total number of turns in the coil. Then,

$$N = N_t\ \ell_g/\ell$$

Also, the total flux across the gap is $\Phi = B\ (2\pi r)\ \ell_g$.

Now equation (B.12) can be rewritten as:

$$E = \Phi(N_t/\ell)\ v = \Phi N_L\ V \qquad (B.13)$$

where N_L is the number of turns per unit length. E_{rms} is obtained by replacing v by v_{rms}. For the velocity given by equation (B-4):

$$v_{rms} = \omega p(\omega)\ a_m/\sqrt{2} \qquad (B.14)$$

and

$$E_{rms} = \Phi N_L\ \omega\, p(\omega)\ a_m/\sqrt{2} \qquad (B.15)$$

B.4 DAMPING

The force resisting the motion of the magnet is:

$$F = i\ B\ N\ 2\ \pi\ r \qquad (B.16)$$

where i is the current flowing in the wire of the coil. This current is simply the current that the emf, E, will drive through the total resistance, R_l, of the coil and an external load. Thus,

$$F = E\ B\ N\ 2\ \pi\ r/R_L$$

$$= N^2\ B^2\ (2\ \pi\ r)^2\ v/R_L \qquad (B.17)$$

In equation (B.1) the damping force is represented by the term bx which is proportional to velocity. Therefore, the damping coefficient due to the electrodynamic action is:

$$b = (2\ \pi\ r\ N\ B)^2/R_L = (N_L \Phi)^2/RL \qquad (B.18)$$

B.5 NUMERICAL EXAMPLE

To estimate the order of magnitude of the power that could be generated by an electrodynamic converter, the rms acceleration figure of 1.4 g for class 4 track has been used. The rms acceleration on class 6 track will be assumed to be four times smaller following Table A.1. Car-body accelerations will be as much as ten times smaller. An oscillatory system driven at its resonant frequency will be assumed with damping at 1/4 of the critical value. Under these conditions equation (B-9) becomes:

$$P_{avr} = \frac{a_m^2 m}{\omega_o} \qquad (B.19)$$

For a mass of 1 kg and a resonant frequency comparable to the resonances found in the truck [Nance (1980)], say 50 Hz, the power is 1.22 watts.

The specifications outlined in section 3 set an upper limit of 15 kg on the power source package. A 10 kg mass could be considered an upper practical limit, in which case the power would be 12 watts. On class 6 track the same system would deliver 0.8 watts. These results assume that the power converter is mounted on the truck. A car-body location would give power levels of the order of 0.12 and 0.008 watts for the two types of track.

It should be noted that reducing b increases the power delivered. However, decreasing b to zero does not give infinite power because, as b decreases the amplitude of the deflection approaches infinity, theoretically. The equations used here would cease to be valid when the spring became solid.

A resonator delivers maximum power to the damping mechanism at the resonant frequency. Therefore, the calculations represent a best case with respect to frequency. However, there are distinct resonant responses in the freight-car suspension, and a device would be tuned to the particular suspension system. The damping at 1/4 of the critical value corresponds to a Q of 2 or a fractional bandwidth of $\frac{1}{2}$, which, for a resonant frequency of 50 Hz would mean at least half of the peak power would be generated for frequencies between $f = f\ (1 + Q/2)$ and $f = f\ (1-Q/2)$, that is 38 and 63 Hz.

Assume a total flux Φ of 1500×10^{-6} webers. This value is typical of the flux produced in the gap of a good quality loudspeaker magnet. Higher values are possible. At resonance (B-15) becomes

$$E_{rms} = \Phi N_L\ m\ a_m/\sqrt{2}b \qquad (B.20)$$

which reduces to

$$E_{rms} = \sqrt{2}\ \Phi N_L\ a_m/\omega_o \qquad (B.21)$$

for the case of $b = m\ \omega_o/2$, discussed above. The previously described mechanical system, with $a_m = 2$ g and $f_o = 50$, will give an E_{rms} of $1.3 \times 10^{-4}\ N_L$. To have an output voltage of, say, 12 volts will require 9×10^4 turns per m. The maximum displacement, d_m, calculated from equation (A.4) at resonsance and with the same

damping conditions as above, would be 2 a_m/ω_o^2 = 0.4 mm. Thus, a gap, ℓg, 1 cm long would required a 900 turn coil. A multi-layer coild should be possible. If it is desirable to reduce the winding density or increase the voltage, stronger magnets should be used. Also, it is possible to create several coil/magnet units within the total mass-spring values.

Again, it is important to note that these figures apply to the class 4 track and a truck-mounted device. A body mounting will reduce the voltage by 10, or conversely require ten times as many turns on the coil to obtain the same voltage. On class 6 track the output voltage would be reduced by a factor of 4.

As indicated in Figure A.5, the vibrational energy will be contained in a band around the resonant frequencies of the suspension. Most of this band would be passed by the frequency response of the mechanical resonator described here. That is, its Q would be lower than that of the suspension. Broader band responses could be devised by coupling several mechanical resonators, but the increases in energy extracted would probably not warrant the additional complexity.

B.6 ASSESSMENT

Calculations in Sections A.3 and B.5 show that, in principle, a converter employing a mass of 10 kg would deliver power of the order of 12 watts on class 4 track, but only 0.8 watts on class 6 track at 40 km/h. It should be noted that the calculations are based on the maximum track-profile variation permitted in a given class.

The advantages of the linear electrodynamic converter are:

(1) Simple construction. A small number of components are needed.

(2) Highly developed technology. All required electrical and fabrication skills are highly developed in other applications. Engineering of a device would be necessary, since no product manufactured for this application was found. Pertinent technologies are found in the manufacture of geophones, loudspeakers, accelerometers.

(3) The technique is theoretically capable of meeting power supply requirements within the guideline constraints on weight, size, etc.

(4) Potentially rugged and sealable against all environmental factors. There will be some trade-off between ruggedness and sensitivity in the mass-spring system.

(5) Low source impedance.

Disadvantages and limitations of the electrodynamic principle in this application are outlined below:

(1) Power output proportional to (train speed)^2. Although the electrodynamic converter itself has a linear power transfer, that is the output power is directly proportional to input power, the available input power is approximately proportional to train speed squared. The practical consequence is a rapid decrease in delivered power as the train speed decreases.

(2) Performance deteriorates as track condition improves. In any system driven by vibrations, as the track profile becomes smoother the available vibrational energy decreases. With a general trend toward upgrading tracks in order to conserve fuel, the effectiveness of a vibration-driven device will decrease. Furthermore, trucks are being improved to reduce vibration as well. Operation would be marginal on class 6 track in terms of the guidelines in section 3.

(3) Not suitable for body mounting. The comments in item (2) are based on a truck-mounted device. Accelerations on the body will be lower than on the truck. Therefore, only on a class 4 or lower track could one expect adequate performance. Truck mounting implies the inconveniences of interconnection to the body, as outlined in section 4.2.

(4) Power will be delivered as a random function of time, marked by strong bursts and quiet intervals. Energy storage will be needed. Capacitors may be sufficient if the capacity gives a storage time constant longer than the longest quiet interval to be encountered. Otherwise a battery will be necessary.

Despite the attractive features of the electrodynamic converter, its dependence on track condition and the inherent randomness of power delivery make it an uncertain source for an on-board supply. It must be noted that, because of some of the rather arbitrary assumptions that had to be made, the estimates of the expected accelerations could be somewhat imprecise. The accelerations will depend not only on track condition, but on the truck design, type of car, load, etc. Measurements of truck accelerations, of the type shown in Figure A.5, on Canadian tracks would help to resolve this uncertainty.

APPENDIX C

PIEZOELECTRIC CONVERTERS

C.1 INTRODUCTION

Piezoelectricity, from the Greek "pressure electricity," describes the effect exhibited by certain asymmetrical crystals in which a voltage appears across the crystals when pressure is applied to them. The effect is also reversible. When a voltage is applied to a piezoelectric crystal the crystal changes shape. This effect can convert mechanical energy to electrical and, conversely, electrical energy to mechanical [Kettani (1970), Angrist (1982)].

The piezoelectric effect has been known to exist in materials such as quartz, tourmaline and Rochelle salts since the late 1800s. In the late 1940s and the 1950s certain ceramic materials such as barium titanate ($Ba\ Ti\ 0_3$) and lead zirconate-lead titanate (PZT) were found to yield very high piezoelectric outputs. Furthermore, these materials can be easily molded or pressed into a variety of shapes unattainable with single natural crystals. Being polycrystalline in nature, the ceramics do not have appreciable piezoelectric properties in their original state. Piezoelectric behaviour is induced in these materials by a polarizing treatment called poling. The direction of the electrical and mechanical axes depend on the direction of the dc polarizing field. During the poling process a ceramic element experiences a permanent increase in dimension between the poling electrodes, and a permanent decrease in dimensions parallel to the electrodes. When a compressive force is applied in the poling direction, or a tensile force applied parallel to the electrodes, the voltage that appears between the electrodes has the same polarity as the original poling voltage. Reversing the direction of the applied force reverses the polarity of the voltage. When the force is removed the material returns to its original poled dimensions and the voltage across the electrodes is zero [Vernitron (1985)].

A well-known application of the piezoelectric principle is found in accelerometers, as illustrated in Figure C-1. In this example two

ceramic discs are sandwiched between a mass and supporting base. If the base is accelerated upward, the inertia of the mass creates a compressive force on the ceramic discs. Downward acceleration of the base causes a tensile force. As shown, the discs have been mounted such that the applied force produces voltages of opposite polarities across the discs, which are connected in parallel. This arrangement allows the base and the mass to be at ground potential. Two or more discs could equally well be connected in series to increase the voltage. Of course, the internal impedance would also be increased. The impedance of two identical elements in series is four times that of the same two elements connected in parallel.

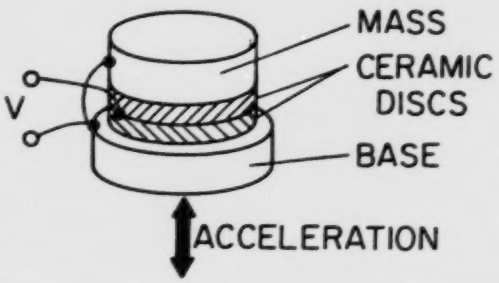


Figure C.1 A piezoelectric accelerometer

Another mechanical-to-electrical application is the high-voltage gasoline ignition system illustrated in Figure C.2. A cam driven by the engine actuates a lever which applies a time-varying force to the ceramic elements which are stacked with like-polarity electrodes facing each other. A device of this type has been used on a small lawn mower motor where it developed ignition potentials of the order of 20,000 volts. A theoretical estimate indicates that, in the configuration of Figure C.2, a 16 cm^3 (1 cubic inch) element subjected to 6.6×10^4 Newtons (15,000 lb/sq.in.) at 60 times per second would deliver 30 watts.

A flexing piezoelectric element called a bimorph has the ability to give much larger deflections for a given applied voltage or, conversely, to give a greater voltage for a given deflection, than can be achieved with single piezoelectric plates. Biomorphs consist of two transversely deformable plates bonded together face-to-face. Application of a voltage to the electrodes on the faces causes the plates to deform in

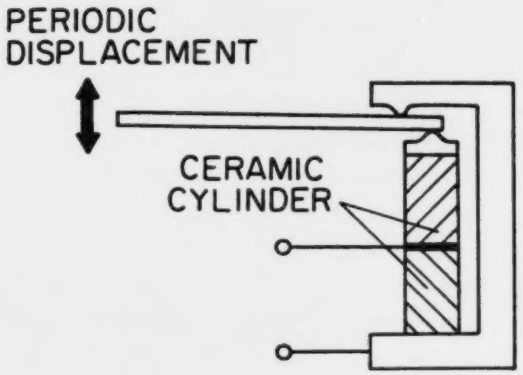


Figure C.2 Piezoelectric power generation by compression

opposite directions, resulting in a bending action, in a manner analogous to the bending of a bi-metallic strip when heated. Conversely, mechanical bending of the element will develop a corresponding voltage between the terminals. Bimorphs have, in effect, a built-in lever which magnifies the piezoelectric effect 10 to 100 times in practice. The performance of a bimorph is greatly influenced by the manner in which it is mounted and driven. Figure C.3 illustrates two of the more common methods used: an end-supported mount with centre drive, and a cantilever amount [Vernitron (1985)].

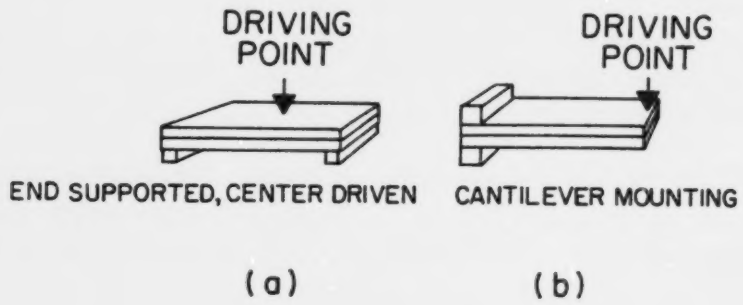


Figure C.3 Typical mounting arrangements for bimorphs

Bimorphs find application as mechanical-to-electrical transducers in "ceramic" phonograph cartridges and "ceramic" microphones. A common application as an electrical-to-mechanical converter is in earphones.

In recent years the piezoelectric properties of polymeric materials have attracted considerable attention [Marcus (1982), Tanaka (1982)]. Of all the polymeric materials investigated, (poly (vinylidene-fluoride)) (PVF_2) exhibits the largest piezoelectric coefficients when appropriately polarized. Furthermore, its piezoelectricity is strong compared to crystalline materials. PVF_2 is easy to handle since it is not brittle, is relatively easy to form into large-area flexible sheets, and has a low density. In contrast, ceramic materials are brittle, heavy and tend to be more difficult to manufacture.

The conventional poling process involves electroding both surfaces of the polymer film, subjecting the film to electric fields of the order of 10^6 V/cm at a temperature of between 80°C and 120°C, followed by cooling with the field applied. The resulting piezoelectric properties depend on the poling time, field and temperature. Other recently developed poling techniques include plasma poling and corona poling.

The PVF_2 material deforms very little when an electric field is created in it. For example, when 100 volts is applied across a 9 micrometres thick film, the dimensional change in the direction of the polymer chain is 3 micrometres per cm of length. However, as in the case of ceramics, a bimorphic structure can greatly amplify the deflection. The motion-amplitude modification ratio of a bimorph structure is roughly the ratio of its length to thickness. Since 6-7 micrometres is the minimum achievable film thickness with PVF_2, a magnification of a few thousand times is easily obtained. In contrast, the minimum thickness of a ceramic bimorph is about 0.5 mm.

Since PVF_2 film can be very thin, a given voltage induces a much larger electric field than for ceramic material. The maximum applicable field without degrading piezoelectric parameters is 300 kV/cm for PVF_2 and 3 kV/cm for PZT.

The high deflection-per-volt properties of PVF_2 bimorphs would appear to argue against their application to power generations. However, the bimorphic elements can be layered to form multimorphs which will give a higher voltage/deflection ratio while still preserving the properties of a polymeric material.

Because ceramic transducers are brittle and stiff, they require smooth flat surfaces for mounting. Damage to large ceramic transducers from mechanical shock or vibration is common. With polymeric transducer elements complex mounts are eliminated by simply gluing the transducer element to the surface. Polymers have a high tolerance for mechanical stress and thus are not damaged as readily as ceramic elements. Polymeric transducers in general have a wide-bandwidth, low-Q response, whereas ceramic devices have a narrow-band, high-Q response.

The main disadvantages of polymeric piezoelectric materials are low piezoelectric strain coefficients and mechanical coupling coefficients. Although the piezoelectric g constant is an order of magnitude higher in PVF_2 than in PZT, it is more difficult to polarize a thick piece of PVF_2. Thus, for high voltage output a multilayer stack is necessary. Polymeric materials experience mechanical relaxation when subjected to stress for a long time. Furthermore, they depolarize, losing their piezoelectric properties, at temperatures of the order of 100°C or higher.

Mechanical-to-electrical conversion applications of PVF_2 include microphones, phonograph pick-up cartridges, ultrasonic sensors in hydrophones and medical imaging, finger-pressure-sensitive keyboards for typewriters and computers, impact detectors and fuses, the latter employing stacks of up to 100 sheets.

C.2 ANALYSIS OF A PIEZOELECTRIC CONVERTER

This section examines the order of magnitude of the voltage and power to be expected from a simple piezoelectric generator, and identifies the important properties of the piezoelectric materials. The converter consists of a disc of piezoelectric ceramic to which energy is applied by means of a force normal to the surface. The device can be visualized as a parallel plate capacitor to which a charge is applied by the effect of the external stress. An equivalent circuit is shown in Figure C.4. The voltage source, V, series capacitor, C, and resistor, R, represent the piezoelectric crystal.

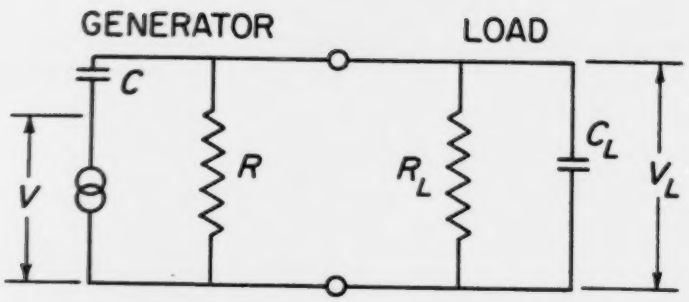


Figure C.4 Equivalent circuit of a piezoelectric generator and its load

Power is to be delivered to a load consisting of R_L and C_L. Since the generator resistance, R, is typically of the order of 10^{12} ohms it can usually be neglected.

The quantity that measures how well the crystal converts mechanical energy to electrical energy is the coupling coefficient defined as:

$$K^2_{33} = \frac{W_{out}}{W_{in}} = \frac{\text{electrical energy stored}}{\text{mechanical energy applied}}$$

The input mechanical energy in the form of a compression force, F, acting on the crystal surface is:

$$W_{in} = \tfrac{1}{2} F \Delta d \qquad (C.1)$$

where Δd is the average distance the crystal surface is displaced. Since F/A is the stress, s, and stress divided by the strain, $\Delta d/d$, is Young's Modulus Y, equation (C.1) can be written as:

$$W_{in} = \frac{1}{2} (s^2/Y) Ad \qquad (C.2)$$

or as:

$$W_{in} = \frac{1}{2} F^2 d/YA \qquad (C.3)$$

The electrical energy stored in the capacitance is:

$$W_{out} = \frac{1}{2} Q^2/C \ , \qquad (C.4)$$

where Q is the charge liberated to the electrodes by the application of the stress. Combining Equations (C.3) and (C.4) yields:

$$Q^2/C = K^2_{33} F^2 d/YA \qquad (C.5)$$

The capacitance of a parallel plate capacitor is:

$$C = \epsilon_o K A/d \qquad (C.6)$$

where: ϵ_o is the permittivity of free space

K is the relative dielectric constant.

Substitution of Equation (C.6) into (C.5) yields the net charge per unit force.

$$Q/F = d_{33} = [k^2_{33} K \epsilon_o/Y]^{1/2} \qquad (C.7)$$

or:

$$Q = d_{33} F \qquad (C.8)$$

The generated voltage is found from the fundamental relationship among charge, voltage and capacitance:

$$V = Q C \qquad (C.9)$$

which, applied to Equation (C-8), gives:

$$V = d_{33} F/C \qquad (C.10)$$

$$= d_{33} Fd/(\epsilon_o K A) \qquad (C.11)$$

The piezoelectric constant g_{33} is defined as the voltage generated per unit applied stress. Thus, from equation (C-11) and the fact that s = F/A, it is seen that:

$$g_{33} = d_{33}/(\epsilon_o K) \qquad (C.12)$$

and:

$$V = g_{33} d s \qquad (C.13)$$

From the equivalent circuit the voltage across a purely capacitive load ($R = R_L = \infty$) would be:

$$V_L = d_{33}F/(Ca + C_L) \qquad (C.14)$$

When R and R_L are taken into consideration, the magnitude of the voltage is:

$$V_L = \frac{d_{33} F/C}{[\,(1 + C_L/C)^2 + (R + R_L)^2/\omega^2 C^2 R^2 R_L^2\,]^{1/2}} \qquad (C.15)$$

where: the force is assumed to be applied periodically with angular frequency, ω

F is the peak value of the force.

For the special case of R very large:

$$V_L = \frac{d_{33} F/C}{[\,(1 + C_L/C)^2 + 1/\omega^2 C^2 R_L^2\,]^{1/2}} \qquad (C.16)$$

The power delievered to the load resistor is:

$$P_L = V_L^2/2R_L$$

A further simplication is obtained by letting C_L be negligible, in which case:

$$V_L = \frac{(\omega C R_L)(d_{33}F/C)}{(1 + (\omega C R_L)^2)^{1/2}} \qquad (C.17)$$

and the power in R_L is:

$$P_L = \frac{d_{33}^2 F^2/C^2}{2 R_L (1 + 1/\omega^2 C^2 R_L^2)} \qquad (C.18)$$

The maximum power is extracted by R_L when $\omega C R_L = 1$. Therefore, the maximum output power is:

$$P_{max} = d_{33}^2 F^2/2C^2 R_L \qquad (C.19)$$

This result can also be expressed as

$$P_{max} = V^2_{rms}/R_L = \omega C V^2_{rms} \qquad (C.20)$$

since $V^2_{rms} = (d_{33} F^2/2C^2)$ from equation (C.10) and the assumption of a sinusoidal force. In terms of the dimensions of the piezoelectric material, equation (C.20) can be written as:

$$P_{max} = \omega d^2_{33} F^2 d/2\epsilon_o KA$$

$$= \omega d^2_{33} s^2 Ad/2\epsilon_o K \qquad (C.21)$$

since $s = F/A$. Note that P_{max} is proportional to the volume, Ad, of the piezoelectric material for a given applied stress.

Some properties of piezoelectric materials are given in Table C.1.

TABLE C.1

PROPERTIES OF COMMON PIEZOELECTRIC MATERIALS

	k_{33}	d_{33}	g_{33}	Y_{33}	K
Quarts	0.10	2×10^{-12}	58×10^{-3}	7×10^{10}	4
Rochelle Salt	0.90	150×10^{-12}	90×10^{-3}	2×10^{10}	350
Ba Ti 0_3	0.50	190×10^{-12}	12×10^{-3}	11.2×10^{10}	1700
PZT-4	0.70	289×10^{-12}	26×10^{-3}	6.6×10^{10}	1300
PZT-5	0.71	374×10^{-12}	24.8×10^{-3}	5.3×10^{10}	1700
PVF_2		39×10^{-12}	28×10^{-3}	0.27×10^{10}	15

Note that in Table C.1 the first subsript refers to direction 3, the direction in a crystal along which forces cause a piezoelectric response. The second subscript 3 indicates that the response is in the same direction. The units of d_{33} are metres/volt or coulombs/Newton, units of g_{33} are volt-metre/Newton, and units of Y are Newtons/m^2, while k_{33} and K are ratios. In the case of bimorphic modes of operation, the quantites of interest relate stress in one direction to the piezoelectric response in an orthogonal direction. Table C.2 gives the appropriate quantities for some piezoelectric materials in the bimorph configuration.

TABLE C.2

PIEZOELECTRIC PROPERTIES OF THE BIMORPH CONFIGURATION

	d_{31}	g_{31}	Y_{11}
Ba Ti 0_3	78×10^{-12}	5.2×10^{-3}	11.6×10^{10}
PZT-5	171×10^{-12}	11.0×10^{-3}	12.0×10^{10}
PVF_2	24×10^{-12}	170.0×10^{-3}	0.3×10^{10}

To obtain numerical values for a piezoelectric generator consider a PZT-4 ceramic wafer 2.5 x 2.5 x 2.5 cm^3 in the accelerometer mode of operation with a peak oscillatory acceleration of 2 g. From equation (C.21) the output power will be 0.35×10^{-3} W. The voltage across the crystal, given by equation (C-13), would be 203 V peak, and the load resistance $R_L = 1/\omega C$ at a frequency of 50 Hz would be 11×10^6 ohms.

To obtain 1 watt in the accelerometer configuration a 534 kg mass is needed.

A compression mode device will required 2.10×10^4 Newton (4724 lb) force applied 2.5 times per second. This is approximately the restoring force obtained by a 1.0 mm (0.4 inch) displacement of one spring set in a freight car suspension system. The rate of application has been taken as the approximate resonant frequency of the car mass and spring system. The voltage across the piezoelectric element will be 2×10^4 volts and the impedance approximately 220 megohms. (The

impedance has risen because the frequency is 2.5 Hz, a value appropriate for the spring oscillations.)

The voltage generated by a bimorph configuration is:

$$V = (3/16)\ g_{31}\ Y\ (t^2/L^2)\ x$$

where: g_{31} is the piezoelectric factor for voltage in the 3-direction due to stress in the 1-direction, in Vm/N

Y is Young's modulus of the material

t is the thickness

L is the length

x is the deflection.

Typical values for PVF_2 are g_{31} = 0.17 Vm/N, t = 30 micrometres and Y = 2.7 x 10^9 N/m^2. For L = 3 cm and x = 1 cm, V = 0.86 volts. Layering, say, 12 sets of bimorphic sheets would give 10 volts. The capacitance of a unit of width 1 cm is 1400 x 10^{-12} F, which corresponds to an optimum load resistance of 2.8 megohms. If 120 layers of tnis bimorph unit were used, the voltage would be 100 V and the thickness 3.6 mm. A width of 10 cm would decrease the capacitance to yield a 0.2 milliwatt output power for a sinusoidal deflection of peak amplitude 1 cm at a frequency of 50 Hz. This deflection is probably excessive for the frequency from a mechanical point of view. Lower frequencies mean higher impedances. The internal impedance of the device described above would be 28 megohms. Increasing L causes the voltage to decrease by $1/L^2$ while the capacitance increases by L. Thus, it is clear that impractically large structures would be needed to approach a 1 watt output.

C.3 ASSESSMENT

The accelerometer-based converter has the following advantages:

(1) A highly developed technology exists. Piezoelectric ceramics are readily available. Piezoelectric

accelerometers have been manufactured for many years and have reached a high degree of sophistication.

(2) Ruggedness. Accelerometers have been developed to withstand very high shocks and impacts of the order of 100 g.

(3) Sealable. Piezoelectric accelerometers are completely sealable against environmental factors.

(4) No moving parts. (Movement of the mass as it deforms the piezoelectric material is microscopic.)

Despite the good features, the calculations above indicate that the accelerometer-mode converter cannot deliver the desired power. For example, a ceramic element of dimension 2.5 x 2.5 x 2.5 cm^3, loaded by a 10 kg mass and subjected to a peak acceleration of 2 g at 50 Hz, as would be expected on a class 4 track, would produce a maximum deliverable power of 0.35 mW. Furthermore, this power would be delivered at 203 volts across an impedance of 11 x 10^6 ohms. A major disadvantage of piezoelectric devices, in addition to the low power output, is the high voltage and extremely high impedance level at which they must operate.

In the compression mode with a force applied to the same ceramic element by means of a mechanical device, 1 watt of output power would require 2.1 x 10^4 Newtons (4724 lbs force), applied 2.5 times per second. Such forces could be achieved in the suspension system by, for example, placing the ceramic element between the end of a suspension spring and the truck, or bolster. Displacement of one end of a spring by 1.0 mm (0.4 inch) corresponds to a restoring force of approximately 2 x 10^4 Newtons. However, in this mode 1 watt would be delivered to the 220 megohm resistance by a potential difference of 2 x 10^4 volts. It is clear why compressive mode devices are of interest as high voltage generators. Changes in the dimensions of the element, for example decreasing the thickness and increasing the area, would improved matters by lowering the impedance and voltage, but not by the orders of magnitude necessary to make a practical system for the train application.

The bimorphic principle changes the relationship between force or displacement and voltage output. However, none of the schemes explored, including multiple-bimorphs, would adequately overcome the problems of low power, high voltage and high impedance.

Piezoelectric energy conversion is considered to be impractical for power levels of the order of 1 watt in this application, but could be of interest at power levels of less than 1 mW.

As with all devices based on vibrational energy, the output power from a piezoelectric device will vary as the square of the train speed. In this connection it should be noted that all figures quoted above were based on the class 4 welded-track condition, and power levels would be significantly lower on smoother tracks.

APPENDIX D

WIND POWER

D.1 INTRODUCTION

The extraction of energy from the wind is a centuries-old energy conversion technology. Early techniques are typified by the Dutch four-arm windmills while in the late 19th and first half of the 20th centuries the multi-blade fan was a common sight on North American farms as the motive power for pumping water. In recent times the search for alternate energy sources has sparked renewed interest in wind power. Propellers with two and three metre length blades have been developed for individual home and farm use. Experimental large-scale systems employing propellers tens of metres in diameter have been built to generate power on a commerical scale. Vertical-axes systems which respond to winds from all azimuthal directions have been developed in this century.

Because propeller and turbine wind-energy converters operate in winds of from 10 to 50 km/h, it is of interest to explore the possibilities of exploiting the apparent wind created by the motion of the train through the air.

D.2 ANALYSIS

The power available in the wind is the flux of kinetic energy of the air molecules through the cross-sectional area presented by the apparatus utilizing the energy. This flux is $\dot{m}V_w^2/2$, $\dot{m}$ being the mass flux through the cross-sectional area, A. In terms of the air density, ρ, $\dot{m} = \rho A V_w$ and the power becomes $P_w = AV_w^3/2$. For all practical purposes the ρ is fixed, being only 16 per cent lower at 1500 m (5000 ft) than at sea level. The sea-level value, 1.225 kg/m^3 (0.0765 lbs/ft^3), will be used here, and yields an available power of $0.6125 \times A \times V_w^3$ watts when A is in m^2 and V_w is in m/sec ($5.05 \times 10^{-3} \times A \times V_w^3$ watts when A is in ft^2 and V_w in mph). The dependence of the available power on V_w^3 makes a wind-power source very sensitive to wind strength.

In practice, it is not possible to remove all of the available power from the wind as this would imply bringing the moving air to rest. For purposes of analysis, the wind turbine is represented as an actuator disk which decelerates the incident wind from a velocity of V_w to an exhaust veolocity, V_e, as shown in Figure D.1. The speed retardation is expressed in terms of an induction factor, sometimes called the interference or perturbation factor, which is defined as $a = 1-(V/V_w)$, where $V = (V_w-V_e)/2$, the velocity at the disk. Also, $V_e = (1-2a)\ V_w$, which means that the maximum value of a is 1/2, in which case $V_e = 0$.

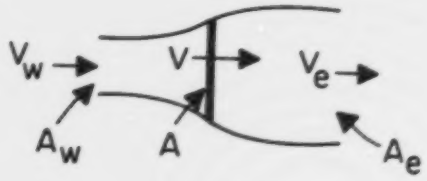


Figure D.1 Schematic representation of wind flow through an actuator disk of cross-sectional area A

The power output is the loss of kinetic energy in passing through the actuator disk. Thus,

$$P_w = \rho\ A\ V\ (V_w^2 - V_e^2)/2$$

which can be expressed in terms of a as

$$P_w = 2\ \rho\ A\ V_w^3\ a\ (1-a)^2 \qquad (D.1)$$

Equation (D.1) has a maximum when a = 1/3, which yields a maximum extractable power of $(8/27)\ \rho\ A\ V_w^3$

A frequently used measure of wind-turbine effectiveness is the power coefficient Cp, defined as:

$$C_p = \frac{\text{actual power developed}}{\rho\ A\ V_w^3\ /2} \qquad (D.2)$$

The theoretical maximum value of C_p is then $4a(1-a)^2$ at $a = 1/3$, that is $(16/27) = 0.593$, or approximately 60 per cent. As a function of a, C_p varies from 0.5 to 0.593 and back to 0.5 for $0.2 < a < 0.95$, but falls rapidly to zero for $0.2 < a < 0$.

In Figure D.1, the entrance to the stream tube is shown as smaller than the actuator disk area, A, because the decrease in velocity from V_w to V must be accompanied by an increase in the cross-sectional area. Similarity, the area of the exhaust tube is greater than A. Thus, $A_w/A = 1-a$ and $A/A_e = 1-2a$. For a turbine in free space, this is of no consequence, since A_w is simply the effective cross-section. However, if a turbine is to be placed in a housing, the expanson requirement will make the turbine uni-directional with respect to wind velocity, an important factor in a freight-car installation.

The factor C_p is not the efficiency of a turbine, which should be expressed as the power output from the kinetic-energy flux across the entrance aperture, A_w. Thus, efficiency is $4a(1-a)$, which, for $a = 1/3$ and maximum C_p, is $(8/9) = 0.89$.

The power delivered by various rotor types and configurations can be written as:

$$P_w = C_p \, A \, V_w^3/2 \qquad (D.3)$$

where: A is the area interrupted by the rotor

C_p is the appropriate factor for that rotor type.

References used in this section are Auer (1979) and Sorensen (1983).

D.3 TYPES OF TURBINES

Wind turbines can be classified as horizontal-axis or vertical-axis turbines. In the former case the actuator disk is normal to the air flow and rotation is about a horizontal axis. In the latter, the rotational axis is perpendicular to the wind flow. The principal characteristics of these two classes are discussed below [Auer (1979)].

Horizontal Turbines

The horizontal-axis turbine is the propeller type, of which the Dutch windmill, mulit-vaned farm windmills and the two- or three-bladed propellers of the same aerodynamic shape as aircraft propellers, are the common examples. The major characteristics of the propeller are:

(1) It must face the wind. That is the plane of the rotor is perpendicular to the wind and, therefore, the rotor has to be moved into the correct direction as wind direction changes. In small machines this is done automatically with a vane; in larger systems an external means must be provided for turning the rotor into the wind.

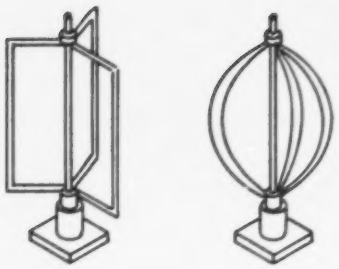
(2) It can have a high blade-tip/wind speed ratio, yielding a relatively high rotational speed which is desirable for electrical generation.

(3) Aerodynamic losses are small, making it the most efficient type of wind turbine known.

(4) It may have two or three blades, or many. This determines its torque-speed characteritics.

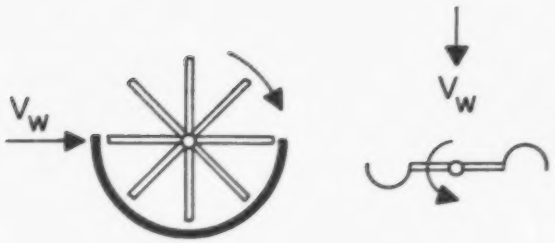
Vertical-Axis Turbines

Many different designs of vertical-axis machines have been built, although most are variations on three basic types, namely the lift type, the drag type and the turbo type. The lift type uses blades of airfoil profile with their span arranged longitudinally parallel to the axis of rotation. The blades may be straight or curved and may be of fixed or variable incidence. Figure D.2 shows a well-known member of this type, called the Darrieus rotor, with its egg-beater appearance. In recent years the National Research Council of Canada has developed an improved version of this type of rotor. The drag type is characterized by the cup anemometer and the simple paddle wheel shown in Figure D.3. The turbo has some features of a steam, water or gas turbine where a momentum change occurs in the flow between adjacent curved blades, rather than by a force acting on a surface. One example is the Savonius rotor shown in Figure D.4. This configuration acts like a two stage turbine at least during part of a revoluton



(a) (b)

Figure D.2 The Darrieus rotor



(a) (b)

Figure D.3 Drag-type turbines: (a) the paddle wheel, (b) the cup anemometer

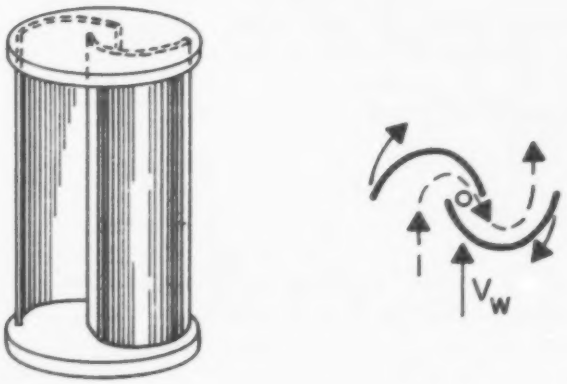


Figure D.4 The Savonius rotor

when the wind impinging on the concave windward side is deflected through the gap at the centre onto the back of the side which is convex to the wind. This action decreases the otherwise negative pressure that would occur in the region behind the convex blade. Another example of the turbo principle is the Banki wheel in Figure D.5.

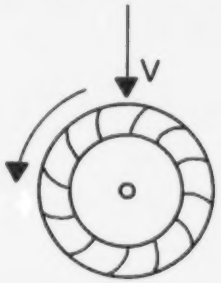


Figure D.5 The Banki wheel

While the vertical-axis machines do not fit directly into the stream-tube representation of Figure D.1, the fundamental principle of extracting power by reducing the kinetic energy of the wind is valid. The basic formula is correct with C_p appropriate to the type of rotor.

The main characteristics of the vertical-axis turbines are:

(1) Because the blades or vanes rotate about the vertical axis, these types deliver power with winds from any azimuthal direction. No tail vanes or positioning equipment is needed.

(2) The generator can be mounted in the base. That is, the turbine support structure does not have to support the generator or mechanical linkages to a base-mounted generator as is necessary with horizontal-axis systems.

(3) Blade-tip speed/wind speed ratio depends on whether the unit is a lift or drag type. The lift type can have a high ratio as for a propeller and will, therefore, turn at a high rate. With the drag type the speed of the tip cannot outrun the "fluid" when travelling in the same direction. The

Savonius rotor can have this ratio slightly higher than unity.

(4) The Darrieus rotor is not self-starting, while all of the other types mentioned here are.

Table D.1 compares the maximum C_p values of several types of wind turbines. Also noted is the blade-tip speed/wind speed ratio, λ, at which the maximum C_p occurs [Prenis (1975), Kentfield (1983)].

TABLE D.1

POWER COEFFICIENT AND BLADE-TIP/WIND-SPEED RATIO

	C_p(Max)	λ
Aerodynamic Propeller, 2-Blade	0.45-0.5	5.5
American Multi-blade Fan	0.30	0.9
Dutch 4-arm Windmill	0.17	2.5
Darrieus rotor	0.55	6.0
Savonius rotor	0.15	0.8
Delta Turbine	0.38	1.8

Wind energy concentrators and augmenters can be employed to enhance the wind-turbine performance. Wind speeds are locally increased by reduction in area, the Venturi effect, or by directing the flow around an obstacle such as the edge of a flat plate or cylinders. Another approach called "shrouded turbines" uses an expanding diffuser in the exhaust stream to reduce the pressure immediately behind the rotor. Vortex-type concentrators make use of the low-pressure, high-velocity area developed with decreasing radius in a free vortex. Concentrators and augmenters can improve the performance of wind turbines by factors of up to 2 for shrouds, and higher with vortex concentrators.

Another aspect of wind turbine operation is that there is a minimum speed above which useful power is developed and below which the rotor is simply balancing the mechanical and aerodynamic losses or is stalled. For most types of wind turbines this speed, called the cut-in speed, is between 8 and 14 km/hr (5-9 mph).

Some unconventional wind-power conversion schemes have been encountered. One would use an acoustic resonator, a single pipe from a pipe organ for example, which is excited by the wind moving across its open end. At a point in the resonator where the mechanical vibrations are strong a piezoelectric or electrodynamic "microphone" would be attached to produce an electric signal. Power levels are low, milliwatts at best. Another system being developed for high levels of power uses the wind to drive a spray of charged aerosol particles against a strong electric field [Mitchell (1985)]. A need for a source of aerosol and a strong electric field rule out this idea for frieght cars.

The piezoelectric properties of PVF_2 polymers have been used in the vanes of Savonius- and Darrieus-type experimental windmills [Schmidt et al (1983)]. The vanes are PVF_2 bimorphs and power is generated by the flexing of the piezoelectric material during rotation. A large area is needed for significant power generations, and the high-voltage/high-impedannce problems of piezoelectrics are present. While the idea eliminates the need for a rotary generator, it does not eliminate the rotating vanes.

D.4 ASSESSMEMT

Wind-driven generators have some very attractive features:

- they can be mounted on the body of the freight car
- they can deliver adequate power within the size constraints of section 3 at moderate train speeds
- their power output is not affected by the track condition, except indirectly because track condition will limit the maximum speed of the train
- technology is well established. However, engineering development is needed to address the specific needs of the railway application.

Accompanying these attractive features are a number of problem areas inherent in wind-powered systems.

- Propellers and turbines tend to be less robust than the equipment normally found on freight cars. Protective enclosures and mounting arrangements will have to be developed.

- Exposed moving parts. Because the turbine assembly must be open to the wind an environmentally sealed unit is impossible. Therefore the individual turbine components must be resistant to environmental effects.

- Wind turbines simply convert the motion of the air to a rotary motion. Some form of electric generator or alternator must be employed, and that introduces additional reliability and maintenance considerations. In principle, the generator unit could be sealed against the environment except for the linkage to the turbine. Here is a place for innovative solutions to the generation and mechanical-coupling problems, especially since the required output power levels are low and some losses in the coupling or generation process could be tolerated.

- Power output is dependent on the cube of apparent-wind velocity. This means that the wind-powered source is the most sensitive to train speed of all the speed-dependent techniques. Furthermore, there is a minimum speed, in the range of 8 to 14 km/h (5-9 mph) for most types of turbines, below which useful power is not generated.

- Apparent-wind direction can vary when it is a combination of train motion and natural wind. If the wind turbine is directional, as in the case of a propeller whose axis is fixed parallel to the tracks, then only the component of wind parallel to the tracks will produce power. Because of the V^3 speed dependence, decreases in the resultant apparent wind due to following winds could be important, especially at low train speeds. For speeds of 40 km/h (25 mph) and higher, natural wind would be a secondary effect. Another approach is to use non-directional turbines of the type that rotate about a vertical axis. Shrouded horizontal-axis turbines are another possibility.

- Horizontal-axis turbines have the highest efficiency, but have a preferred sense to the wind. Augmenters and concentrators also make turbines uni-directional. The railway application requires turbines which work in both senses of car travel. The Well's self-rectifying, horizontal-axis turbine [Raghunathan and Tan (1984)] might be worth further study in this connection.

- Blockage of the air stream or the jamming of the rotor by foreign objects is a highly likely failure mode for a wind generator on a freight car. Objects such as newspaper pages, articles of clothing, leaves, snow, etc, can block an air passage or jam the turbine. Twigs, gravel or ice build-up can interfere with the rotation of a turbine. Obviously, a sturdy protective grill work of some sort will be needed to deflect flying debris, prevent paper or cloth from being inserted into the air path, and yet allow an adequate flow of air. The finer the mesh of the grill, the larger the entrance area will have to be for a given total air flow. The protective structure and grill will also have to be sufficiently rugged to stand up to the physical abuse they will receive in the rail environment. Whether this can be done is an open question at the moment.

It is clear that despite the very attractive features of wind power, there are a number of practical problems arising in the freight-car application which must be overcome. Also, the fact that there are moving parts in a wind-turbine power source make the reliability and maintenance characteristics less favourable than those of the techniques using solid state or completely sealable devices.

An aspect of on-board wind power which must be considered further, and for which there appears to be little information available, is the aerodynamic effects of the car body and the train consist. One would expect a shear across the wind stream due to drag at the car body surface, which would reduce the average velocity of the air stream. A wind perpendicular to the car surface would split, with part of the air passing under the car and the rest passing over it. This will cause vertical wind components downward and upward from a zone of no vertical movement part way up the side of the car. Local turbulence

caused by the car body could also be a problem. On the other hand there may be locations where aerodynamic effects create, or could be caused to create, an enhanced air flow not greatly affected by the external natural wind. Any concentration/augmentation effects would have to work in both directions of travel without requiring modification to the turbine assembly. A study of the local aerodynamic environment of freight cars will be necessary before firm statements can be made regarding turbine type and preferred location on the car.

APPENDIX E

THERMOELECTRIC CONVERSION

E.1 INTRODUCTION

Thermoelectric-energy conversion is based on a bulk effect in solid material. Whenever heat flows through a solid, electric charge carriers in the solid are swept along and a voltage is developed between the hot and cold ends. This phenomenon, called the Seebeck effect after the man who first studied it over 150 years ago, is most familiar in thermocouples which are used to electrically measure temperature. Thermocouples are found in the thermostats of electric ovens, electric thermometers and as the temperature sensing element in process control systems. While the individual thermocouple delivers only a fraction of a watt, large numbers of thermocouples can be connected together, in parallel across the heat source and sink, to form thermopiles capable of delivering up to hundreds of watts. The electrical outputs may be connected in series, parallel, or a combination, to obtain the desired terminal voltage.

Some present-day applications illustrate the state of development. Thermoelectric generators powered the Pioneer and Voyageur crafts which sent back the pictures of Saturn and Jupiter, the Viking Mars Lander, the USSR unmanned moon rover, and many satellites [Bennett et al (1983)]. These systems use a long-life radioisotope as the heat source. A quiet, highly-reliable, 500-watt generator operating from fossil fuels has been developed for the military [Angrist (1982)]. Similar systems using either fossil fuels or radioisotopes as a heat source are used to operate VHF repeaters and telemetering equipment in remote areas, and marine navigation aids such as lights, foghorns and radio beacons [Rosell and Vogt (1978), Benson and Jaydon (1980)]. Thermoelectric generators have proven to be highly reliable, maintenance-free power sources in extremely demanding applications. A significant thermoelectric industry thrives today.

E.2 PERFORMANCE

For given hot and cold junction temperatures, the performance of a thermoelectric generator is determined by three parameters, namely the electrical conductivity, the thermal conductivity, and the Seebeck coefficient. The electrical conductivity, σ, must be high so that the thermoelectric device will have a low internal resistance. The thermal conductivity, k, must be low so that the heat is not too easily transmitted through the material, and the Seebeck coefficient, S, should be as large as possible because the voltage developed is:

$$v = S\,(T_H - T_C) = S\,\Delta T \qquad (E.1)$$

where T_H and T_C are the temperatures of the hot and cold sides of the thermoelectric material. These three parameters are combined into a figure of merit, Z, for the material as:

$$Z = \frac{S^2\sigma}{k} \qquad (E.2)$$

The units of the paramters are: S in V/K, σ in mho/m, and k in W/m.K (K is degrees Kelvin). A good thermoelectric material has a large Z. Figure E.1 shows Z as a function of temperature for several materials used in thermoelectric generators. Typical values of Z are between 1×10^{-3} and 2×10^{-3}. Seebeck coefficients are usually between 100×10^{6} and 250×10^{-6} V/K.

A second figure of merit can be defined as:

$$M = Z\,\frac{T_H + T_C}{2} = Z\,\bar{T} \qquad (E.3)$$

where $\bar{T}$ is the average operating temperature.

For a thermoelectric generator operating between two temperatures, T_H and T_C, the maximum conversion efficiency is:

$$\eta_{mc} = \eta_c\,\frac{(1 + Z\bar{T})^{1/2} - 1}{(1 + Z\bar{T})^{1/2} + T_C/T_H} \qquad (E.4)$$

where $\eta_c = \Delta T/T_H$, the Carnot cycle thermal efficiency. Z is taken as the average value between T_H and T_C. Equation (E.4) is plotted in Figure E.2 for T_H from 400 kto 3,000 K with T_C held at 300 K. In order to achieve the maximum value of the conversion efficiency, the ratio of the load resistance, R_L, to the internal resistance, R_G, must be $(1 + Z\bar{T})^{1/2}$. However, maximum power transfer from source to load requires that $R_L = R_G$. If the generator is operated for maximum power transfer, the conversion efficiency will drop slightly and is given by:

$$\eta_{mp} = \eta_c \left[(4/ZT_H) + 2 - \Delta T/2\, T_H \right]^{-1} \qquad (E.5)$$

The output power from the generator delivered to a load, R_L, is:

$$P_o = I^2 R_L \qquad (E.6)$$

and, from equation (E.1):

$$I = \frac{S\ \Delta T}{R_G + R_L} = S\ \Delta T/2\ RL \qquad (E.7)$$

when generator or load are matched. Thus:

$$P_o = S^2\ \Delta T^2/4\ R_L \qquad (E.8)$$

which becomes:

$$P_o = S^2\ \Delta T^2\ A\ \sigma/4L \qquad (E.9)$$

with the substitution of:

$$R_L = R_G = \frac{L}{\sigma A}$$

where: A is the cross-sectional area of the element

L is the length of the element.

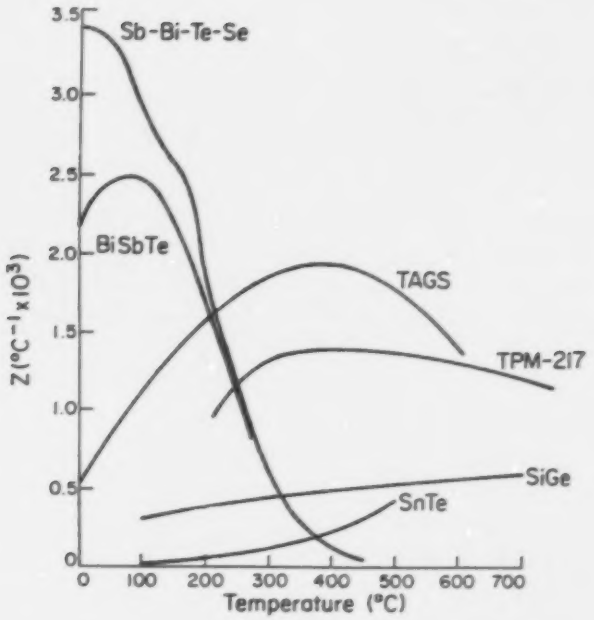


Figure E.1 Figure of merit as a function of temperature for several thermoelectric alloys

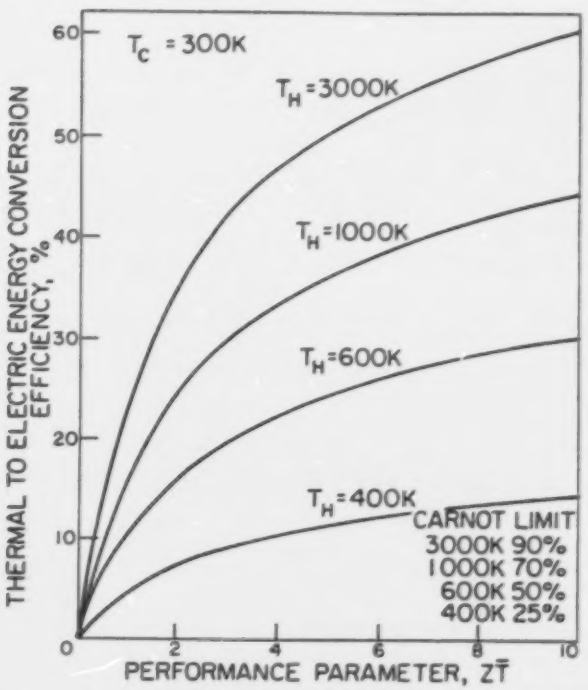


Figure E.2 Energy conversion efficiency as a function of $Z\bar{T}$ for different hot-contact temperatures

Note that the output power depends on the square of the temperature difference.

The best thermoelectric materials are carefully formulated semiconductors which have optimized properties over a specific temperature range, as can be seen in Figure E.1. Since the Seebeck coefficient is only about one-tenth of a millivolt per degree C, many individual thermocouples must be connected together, as shown in Figure E.3, if outputs of several volts are to be obtained. In order to maintain a continuous current, the sign of the charge carriers in alternate elements must alternate from positive to negative. In the p-type material, positive charge carriers (holes) are swept from the hot side to the cold side, while in the n-type material the negative charge carriers (electrons) are swept from the hot side to the cold, resulting in a voltage across each pair equal to the sum of their individual voltages. The total voltage across N pairs is simply N times the pair voltage. Note that both positive and negative terminals are on the cold side, which means that heat is not lost to a hot-side conductor.

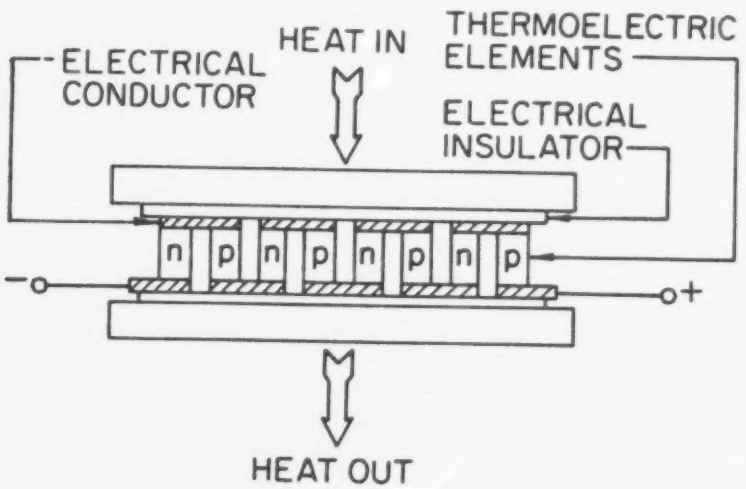


Figure E.3 A thermoelectric generator, or thermopile

References relevant to the analysis of the thermoelectric converter are Angrist (1982) and Sorensen (1983).

Because of their solid-state construction, thermoelectric devices are highly reliable. When failures occur they tend to be either high resistance or open circuit solder junctions due to overheating. Mean time before failure has been found to be better than 100,000 hours at 100°C, and two to three times higher at 20°C.

Thermoelectric devices have successfully met shock and vibration requirements of space vehicles, aircraft and shipboard applications. The devices are strong in both tension and compression, but weak in shear. When used in an environment where there is severe shock and vibration, the devices should be mounted so that they are under compressive loading.

E.3 NUMERICAL EXAMPLE

Consider a themoelectric generator constructed of p-type and n-type semiconductors having similar characteristics. This would be true of 75 per cent Bi_2Te_3/25 per cent Bi_2Se_3 alloy as the n-type and 25 per cent Bi_2Te_3/75 per cent Bi_2Se_3 alloy as the p-type.

For these materials at T = 100°C, S = 160 x 10^{-6} V/K, σ = 0.8 x 10^3 mhos/cm, and K = 0.012 W/cm.K. The length of the element is 1 cm and its cross-sectional area is 1 cm^2. This ratio of length to area is close to the theoretical optimum for these materials.

For the temperature difference of 30°C discussed in Appendix A.1, the power delivered to a matched load is given by equation (E.9) as 0.0046 watts.

Since the area of the element is 1 cm^2, the power per cm^2 is 0.0046. To obtain 1 watt an array of 217 elements would be needed, which means that the hot-contact area would be slightly larger than 218 cm^2, say 250 cm^2. In other words, the thermopile would need a 16 cm x 16 cm (6.3 in. x 6.3 in.) hot-contact area on the bearing casing. Such a large contact area on a conventional roller bearing may not be possible without interfering with the bearing adapter.

The figure of merit is:

$$Z = \frac{(160 \times 10^{-6})^2 \times 800}{0.012} = 1.7 \times 10^{-3}$$

The efficiency of the generator, given by equation (E.5), is 0.01 or 1 per cent.

Finally, the voltage delivered per element is 9.6 mV.

The 218 thermocouples connected in series would give a terminal voltage of 2.1 volts which becomes 1.05 V across the matched load of 0.27 ohms.

Higher voltages could be obtained by using a larger number of series-connected thermocouples with proportionately smaller contact areas. That is, the 1 cm^2 area used in this example could be replaced by 10 units of 0.1 cm^2 area, giving 10 times the voltage and internal resistance but the same delivered power to the matched resistance.

This calculation has been made for typical materials. Other materials could bring about some improvement in performance, but nothing as great as an order of magnitude [Angrist (1982)]. Recent developments in thermoelectric materials have been directed to the goal of increased efficiencies at operating temperatures above 500°C for applications employing radioisotope heat sources [Stapfer (1980), Mullin (1982)]. The principal reason for the very poor performance of the thermoelectric generator is the dependence of the output power on ΔT squared. Thus, while power is available at the hot bearing, it cannot be efficiently extracted by a thermoelectric device because of the low differential temperature between the bearing and the surroundings which would serve as the heat sink. Some improvement might be made by the addition of cooling fins to reduce the cold temperature.

The possibility of using roller bearing heat has been explored in connection with a hot-bearing sensor built into one of the bolts of the journal end cap [Allen (1979)]. This device, called the RF-bolt, is intended to transmit a radio-frequency warning signal if the temperature of the bolt exceeds a preset value. One version of the RF-bolt was to use a thermopile of 466 thermocouple pairs mounted inside the bolt so that the hot contacts received heat from the wall of

the bolt. The hollow interior, the cold side, was to be maintained at a temperature 36°C below that of the exterior by means of a heat exchanger composed of a "heat pipe" and cooling fins attached to the head of the bolt. The proposed scheme would produce 0.25 watts delivered at a terminal voltage of 5 volts. Thermopile contact area was 10 cm^2 (1.6 $in.^2$). For the same thermopile units to produce 1 watt at T = 30°C, an area of 57.5 cm^2 (9.2 $in.^2$) would be required. Thus, using this design one reduces the hot area by a factor of four. The reason for the difference in designs is that the RF-bolt uses a thermocouple element with a Seebeck coefficient two times larger than the values used in the earlier example (that is, two times the voltage and four times the power).

The hot contact area needed with either design will be large. If distributed among modules mounted in several bearing casings, the desired power could be easily produced. This would mean increased complexity and reliablity problems in cabling and connectors, which would tend to counter the advantages of the thermoeletric devices.

E.4 ASSESSMENT

The principle advantages offered by thermoelectric converters are:

- no moving parts (a solid state device)
- highly developed technology supported by an established industrial base
- reliable, mean time before failure is greater than 10^5 hours
- sealable against enviornmental factors
- rugged. Thermopiles have been used in space applications, in military field units, on board ships, and have been mounted on the exhaust ducts of jet engines. However, it is not certain how well current commercial units would stand up to the shock and vibration experienced on the trucks of a freight car.
- power from bearing heat does not depend on the track condition, except indirectly when train speed is limited by the track condition.

Set against these advantages are several practical problems:

- Small temperature difference. The power delivered by a thermopile is proportional to the square of the difference between hot and cold temperatures. The approximately 30°C available between bearing and the external environment is at least an order of magnitude lower than the temperature difference usually employed by thermoelectric converters. Thus, a much larger thermopile contact area is needed for a given power output than would be needed at higher temperatures. Calculations based on typical thermoelectric semiconductor properties indicate that a contact area of 16 cm x 16 cm (6.3 inch x 6.3 inch) would be necessary to generate 1 watt.

- Installation. The large contact area required would mean substantial modification of the bearing housing to accommodate the thermopiles while maintaining its mechanical strength. Distribution of the thermopiles among all of the bearings would reduce the area used at each, but would complicate the installation with electrical wiring to interconnect the thermopiles. Furthermore, inter-bearing cabling could introduce reliability problems.

- Truck mounting. Only the heat of the bearings would have the reliability and continuity needed for an energy source.

- Delayed action. A delay from 20 to 60 minutes can be expected between start-up and the time the bearings reach the temperature required for power generation. Recall that power output falls as temperature difference square; therefore, only when the temperature has risen to a value close to the design temperature will significant power be developed. In contrast, all of the other energy conversion schemes develop their power as soon as the driving mechanism commences to operate.

- It may not be easy to hold the cold end at the ambient temperature because of the amount of heat that must flow out. Therefore, either the temperature difference will be lower than the figures quoted above, or some device such as cooling fins will be necessary.

APPENDIX F

RADIOISOTOPE-THERMOELECTRIC GENERATORS

Although the technology is quite sophisticated, the RGT or nuclear battery itself is quite simple, consisting of a plutonium heat source in contact with the hot surface of a thermopile of the type described in Appendix E. Figure F.1 is a simplified diagram showing the construction of the nuclear battery [G.A. Technologies]. The fuel capsule is 2.5 cm (0.98 inches) in diameter and 5 cm (1.96 inches) in length. The fuel is plutonium -238, which has a half-life of 87 years. Since only a few grams of plutonium are needed, most of the fuel cell is the casing which provides shielding against radiation and containment of the gaseous products produced by nuclear decay.

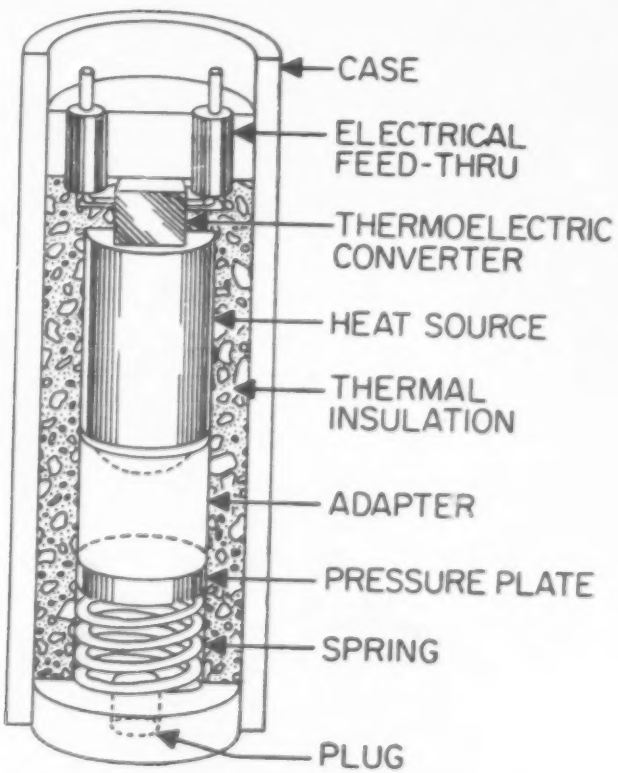


Figure F.1 A simplified drawing of a radioisotope thermoelectric generator (RTG). The walls of the heat source consist of three metal layers.

The specifications of a 2 W RTG are:

- Power output: 2 watts at the beginning, 1.6 watts at 20 years.
- Voltage: up to 12 volts, depending on interconnection of thermopile elements.
- Dimensions: 6.35 cm (2.5 inch) diameter, 15.24 cm (6 inches) long;
- Weight: 2.27 kg (5 lb)
- Fuel: PuO_2
- Thermoelectric converter: PbTe
- Hot junction temperature: 520°C
- Operating temperature range: -50 to 50°C
- Radiation at 10 cm: Gamma - 4 mrem/hr (max)
  Neutron - 3 mrem/hr (max)
- Lifetime: 15-20 years

Nuclear batteries are also made in 0.1 watt and 0.8 watt versions. The manufacturer is GA Technologies in San Diego, California.

The feature of the 2-watt RTG in the context of the railway application is that it meets all of the guideline specifications given in section 3. From a technical point of view it is the ideal power source for the freight-car application.

Furthermore, it delivers power 24 hours per day for 15-20 years without regard for train motion, track condition or the environment. No auxiliary storage is needed. (Large surges for pulse transmission or the operation of a solenoid valve can be provided by capacitors.)

From the point of view of safety, the fuel cell casing is designed to withstand an aircraft crash and fire after 26 years of operation, that is when there is a high internal pressure from gaseous by-products (helium). The capsule can be shot out of a bazooka at a concrete wall

at close range without rupture. It must be able to withstand impacts of 80 g lasting 18 msec on all axes. Since weight would not be a problem on a freight car, the RTG unit could be further encased in an external steel casing.

Plutonium oxide is a ceramic, which means that it presents much less of a hazard than other forms of plutonium should the enclosure be penetrated. The toxicity of plutonium -238 is such that a microgram in the blood stream could be fatal. Despite the hazards, plutonium has been used to power the most reliable cardiac pacemaker system ever built [Greatbatch (1984)].

The principal problems envisaged with RTGs on trains are:

(1) The acceptability of radioisotope material, even in such small quantities and securely encapsulated, on a train. Emotional reactions would probably outdistance the real risks of contamination ever occurring from the unlikely occurrence of a ruptured capsule.

(2) Plutonium is a government-controlled substance. At the end of the RTGs life the plutonium fuel must be returned to a disposal centre. (The lifetime of the unit is determined by the gas pressure build up. In princple, the fuel can be replenished and the cell reused). Usage of plutonuim is tightly regulated and there could be difficulty in obtaining permission for such wide-spread use.

(3) The cost of plutonium is determined by governments. The 2-watt RTGs can be made for less than $100 each in quantities of 1000, plus the cost of the plutonium which depends on the "deal" that can be made. Because it is used only 15 to 20 years , it has a considerable useful life when it is returned to a disposal centre and can be reused. At the moment, one hand-assembled unit costs from $10,000 to $25,000, the range being determined by the deal the customer has been able to arrange for the plutonium fuel.

Despite its ideal technical characteristics, the use of RTG power supplies on trains would be fraught with regulatory requirements and acceptability problems. One aspect that could be pursued is the possibility of using other radioisotopes which are not subjected to the same regulation and are potentially less harmful. Larger quantities might be needed to achieve the same power levels, but RTGs do not appear to pose a size problem at the power levels considered here.

APPENDIX G

SOLAR POWER

G.1 INTRODUCTION

When the sun is overhead, the power available in sunlight reaching the earth's surface is 1 kW/m^2. Light can be converted to electricity directly by means of the photovoltaic effect [Pulfrey (1978), Merrigan (1982)]. Semiconductor devices based on this effect are known as solar cells. Basically, a solar cell is a large semiconductor diode so constructed that light can penetrate into the region of the p-n junction. Silicon is the most commonly used semiconductor material, with small quantities of certain impurities added to create either excess electrons or excess holes (absence of electrons) to form p-type and n-type materials, respectively. Sunlight is absorbed in the silicon, producing both excess electrons and excess holes. In the vicinity of the p-n junction, the inherent electric field separates the holes from the electrons, causing the holes to build up in the p-type material and the electrons in the n-type material. By connecting wires to the n- and p-type regions, these excess charges generated by the light and separated at the junction can be made to flow through an external circuit to provide power.

A typical monocrystalline silicon cell will produce 0.46 V under the load conditions for maximum output power. The current density is 24 mA/cm^2 yielding a power of 11 mW/cm^2. These figures are for 100 mW/cm^2 (1 kW/m^2) illumination. Therefore, the efficiency is 11 per cent. An interesting characteristic of the junction solar cell is that the terminal voltage changes little over a wide range, almost a factor of 10, in illumination. Thus, solar cells are ideal for charging batteries. However, current delivered is directly proportional to illumination.

Since most applications require voltages higher than the inherent junction voltage of a single solar cell, a number of cells are wired in series to form blocks or modules giving the desired voltage. These modules can be assembled into arrays, interconnected in series and parallel, to give the output voltage and current demanded by the load.

In addition to monocrystalline silicon, other forms of silicon, and other materials such as CdS, GaAs and InGaP, are used. Internal electric fields can be created by other than the homojunction p-n cell. For example, at the interface of two different materials such as CdS and Cu_2S a heterojunction is formed with a field which will separate the carriers created by incident light. The features of different cell materials are different conversion efficiencies, voltages, fabrication techniques and costs. Solar cell manufacture is a highly developed industry. Future developments will be directed to continued decrease in fabrication costs and, through perfection of manufacturing techniques with new materials, increased efficiencies. The development of solar cells is driven by the strong interest in electricity from sunlight on the part of industry, government agencies, the military and the space programs [Kazmerski (1981), Iles (1982), Scott-Monck (1982), Trumble (1982), Kamath (1982), Barthelemy (1983)].

Solar power has already seen considerable use by railways [Armstrong (1979), Dichler (1981), IRJ (1983)]. For example, the Southern Railway, the Seaboard Coast Line and the Southern Pacific Railway have installed solar-powered track circuits at locations where conventional ac power is not available. The Atchison, Topeka & Santa Fe Railway in the United States, the SNCF in France, the Australian National Railway, and the Indian Railways have applied solar energy to the powering of remote repeater stations in communications links. The application closest to the one considered here is Southern Rail's installation of Solarex solar panels on 80 cabooses to charge the batteries which operate the rear marker lights. In Canada, solar power is being used increasingly by the Coast Guard to power navigation lights and beacons in remote locations.

G.2 ANALYSIS

The solar flux at a given latitude varies through the day/night cycle and with seasons. Superimposed on these predictable cycle changes are the random variations due to climatic conditions. It is clear the substantially greater storage capacity would be needed in a solar-powered system in order to supply power during the night and during periods of overcast skies which can last for days. Data used in the analysis below come from Pulfrey (1978) and Merrigan (1982).

Because of the variability of the solar flux, it is necessary to consider the average powers available over extended periods and relate these to the energy requirements of the freight car. If 1 watt is required, and the car is considered to be in use and requiring power for 16 hours per day, then the energy requirement of the car is 12 Wh/day or 4.38 kWh/year. With solar cells of 10 per cent efficiency, an incident energy of approximately 44 kWh/year is needed.

In the Great Lakes region, the Maritime provinces and along the 49th parallel to the West Coast, the average solar flux density on a horizontal plate is approximately 150 W/m^2 or higher, and drops to an average of 54 W/m^2 in December. The total daily energy incident on a horizontal plate in June in Southern Canada is about 7 kWh/m^2-day, and in January is about 1.5 kWh/m^2. The annual mean daily isolation for Ottawa is 3.9 kWh/m^2 on a horizontal plate and 5.0 kWh/m^2 on a plate normal to the incident radiation. These figures translate into 1,423 kWh/m^2 and 1,825 kWh/m^2 per year. A quick calculation suggests that the 44 kWh required by the freight car could be supplied by a horizontal collector of 0.031 square metres.

However, the system must be capable of recharging a storage cell in winter when 1.5 kWh/m^2-day is available on average. Horizontal panels would be suitable on box cars, vertical panels would be more appropriate for open-topped hopper cars. At Canadian latitudes verical collectors are almost as effective as horizontal, being superior in winter if facing south. However, because the freight car could have any orientation to the sun, vertical solar panels should be mounted on both sides. For these calculations a factor of 2 will be included to take account of arbitary orientation. Of course, orientation in the horizontal plane is unimportant for horizontal collectors. Quite often the vertical panels will fall in the shade of buildings or other cars, specially in yards. They should have clear exposure when on the open rail. A factor of 2 has been allowed for shading. With these additional considerations and 10 per cent efficient cells, the power requirements of the car could be met in January by panels of 0.36 m^2. In arriving at this figure the packing factor for round cells, 0.88, has been used. Closer packing with hexagonally shaped or rectangular cells is possible. Half this area would be adequate for panels mounted on the roof. It should be noted that there is also a diffuse radiation of

300 Wh/m^2-day in December and January. This diffuse radiation will provide some power even when the panals are not receiving direct solar illumination.

As mentioned earlier, energy storage is needed. In designing solar-powered systems for remote locations it is customary to provide storage capacity sufficient for 15 days operation during the overcast periods. This means 240 Wh in the freight-car case. Conventional rechargeable batteries can provide 24 Wh/kg; therefore, 10 kg of storage battery would be sufficient. Better batteries can give up to 100 Wh/kg and some of the newer rechargeable lithium cells are expected to provide 200 Wh/kg. Therefore, the storage requirements should not pose a weight or size problem, even if somewhat greater reserve capacity were deemed necessary.

Studies of the accumulation of dirt on solar panels and its effect on performance indicate that in an urban industrial environment the output of a solar panel will fall to 78 per cent of its "clean" value in 12 months. Performance can be restored by washing [Sheskin (1982)]. Maintenance in the form of an annual cleaning would seem to be advisable, and the solar panel area should be increased by a factor of 1.3 to 1.5 to compensate for the effects of accumulated dirt between the cleaning of the panels.

Finally, technological developments in the solar cell industry are creating cells with efficiencies higher than the 10 per cent used in these calculations. Efficiencies as high as 18 to 20 per cent have been achieved, but the cells are still relatively expensive. An increase in efficiency brings a proportional decrease in required area.

In summary, the power requirements of the car could be met with a horizontal panel of 0.25 to 0.35 m^2 or vertical panels of 0.5 to 0.6 m^2, using current technology, and in the future with panels less than 0.25 m^2 or 0.5 m^2 in the horizontal and vertial orientations, respectively.

The primary problem with solar panels will be protection from damage. Solarex uses tempered glass which it claims can withstand severe weather, hail, ice and sand [Solarex (1981)]. Protective coverings of transparent Lexan, an extremely strong plastic with a high light transmission, have also been suggested. It should be noted that it is

possible to arrange the cell interconnections so that if one cell is damaged the disruption to the functioning of the rest of the panel is minimized. Cells are mounted in silicone rubber cushions to make them shock and impact resistant. The panels can be sealed against moisture and weather, and operate well over very large temperature ranges. Some degree of progressively diminishing transmission would be expected from scuffing of the protective cover. Solarex panels have been subjected to extensive testing by the Jet Propulsion Laboratory (JPL) in the United States and by the Canadian Coast Guard. It is claimed that the panels meet severe standards for salt spray, immersion, hail, sand, impact and vibration.

The Solarex 2000/12 solar panel has been employed in railway applications [Solarex (1981)]. Its pertinent characteristics under 1 kW/m^2 illumination are:

peak power:	20 W
voltage	open circuit: 21 V, nominal: 14 V
current at nominal voltage:	1.3 A
temperature range	-40°C to 100°C
humidity	prolonged exposure to 90-95 percent at 70°C
dimensions	57.6 cm x 57.6 cm x 2 cm
weight	16.4 kg

These dimensions correspond to an area of 0.33 m^2.

G.3 ASSESSMENT

Solar power as an on-board power source offers the following advantages:

(1) There is adequate power available with a collecting area of the order of 0.5 m^2.

(2) The technology is highly developed and components are available as manufactured products. Improvements continue to be made so that efficiencies are increasing and costs decreasing. (Greater efficiency means smaller area.)

(3) Solar cells are solid-state devices. There are no moving parts. Fifteen to twenty year lifetimes are possible.

(4) Body mounted.

(5) Power delivery is continuous dc when the cells are receiving illumination, and is independent of train speed, track condition, or car weight.

(6) A solar system will recharge its batteries at all times that illumination is available. Thus, cars left idle for days at a time will continue to have fully charged batteries.

(7) Properly packaged solar arrays have been found to be rugged and reliable in other railway applications.

(8) Costs are reasonable now, and can be expected to continue to decrease in the future.

The principal problem areas expected in on-board use of solar panels are:

(1) The solar panel is not so robust as the equipment normally found on freight cars. A transparent protective cover will be required. Manufacturers claim that this is possible with tempered glass or Lexan. Whether the panels have adequate ruggedness for use on freight cars will have to be determined by field testing.

(2) Roof-mounted panels would give adequate power with an area of less than 0.5 m^2. However, side-mounted panels would have to be somewhat larger and two would be needed, one on each side. Flat cars would need special mounting arrangements which would also protect the panels.

(3) Larger energy storage capacity is needed compared to other systems studied. However, the battery size and weight necessary is not prohibitive.

(4) The performance of the panels will deteriorate as dirt accumulates on the surface. Washing will restore the panel to its original efficiency, but this represents a maintenance requirement.

(5) Solar panels and their protective covers of the size considered here could be heavier than the guideline specification. Since the guideline was based on a reasonable weight for one man to handle easily, and since the panel area can be made up of independent modules, this does not seem to be an important factor.

In summary, the use of solar panels as an on-board power source for freight cars should be given very serious consideration.

APPENDIX H

REJECTED TECHNOLOGIES

Several technologies were rejected after a cursory examination because they were clearly not suitable.

Ferroelectric power generation is based on the rapid variation of the dielectric constant of some materials in the neighbourhood of their Curie point temperature. Power generation requires heat cycling of the material about the Curie point [Angrist (1982), Olsen (1984)]. Thus, the system requires either a periodic heat source or a periodic exposure to the source. The technology appears to be still at an experimental stage and did not appear to offer any special advantages in the railway application.

The Nernst effect has received considerable theoretical study as a means of converting heat to electricity [Angrist (1982)]. The effect makes use of the interaction of thermal and magnetic fields in semiconductors and semimetals. Efficiencies at present are of the order of a few per cent achievable only with high temperature differences and high magnetic fields. Nernst-effect generators are still experimental and offer no advantages to this application.

Thermionic energy converters are vacuum diodes employing the thermionic emission of a cathode to convert heat to electricity [Angrist (1982)]. Electrons in the cathode material must be given sufficient energy from an external heat source to allow them to escape from the cathode and reach the anode. Thus, thermionic generators are high-temperature devices, usually requiring temperatures in the 1000s of degrees. Although the technology is well developed, it appears to be better suited to the production of kilowatts of power from large heat sources, and is unsuitable for the railway application.

Fuel cells are batteries in which the fuel and oxidizer are stored external to the battery [Angrist (1982)]. This technology has received considerable attention as a candidate power source for electric automobiles. It has also been of interest as a high power source for electric utilities. An important feature of fuel cells is that they can

have a relatively high efficiency without requiring rotating machinery. However, the need to replenish a fuel supply, even if the fuels were in solid interchangeable packages, represents a maintenance requirement not significantly different from replacing or recharging conventional batteries.

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ADDENDUM TO

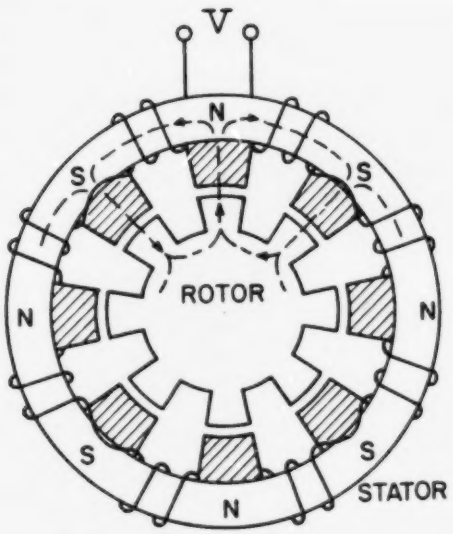
ON-BOARD POWER SOURCES FOR FREIGHT CARS

G.J.M. Aitken

The purpose of this addendum is to provide additional material for Section 4.1 and Appendix A.5 on the subject of permanent magnet (PM) and variable reluctance (VR) alternators. The concept was mentioned briefly in Appendix A.5 where a PM alternator incorporated into the bearing end-cap was suggested. There was no further elaboration of the idea in the report.

The PM alternator employs one or several permanent magnets on a rotor, arranged so that their flux lines cut the windings of a stator. There is no need for field excitation, commutators, nor slip-ring contacts.

The VR alternator has the source of magnetic field and the winding in which the voltage is induced mounted in the same structure, usually a stator. The magnetic circuit is completed through the rotor which is toothed or crenellated. As the rotor revolves, the air gaps between the pole pieces of the stator and the teeth of the rotor vary periodically. This varying air gap causes the reluctance of the magnetic path to vary and, hence, an alternating flux is produced. The winding on the stator pole piece experiences the varying flux and a voltage is generated. The advantage of the VR alternator is that the winding and magnetic source are located in one unit, and the rotor is simply a piece of toothed magnetic metal. A magnetic field can be produced by either a field coil excited externally or by permanent magnets. One disadvantage of the VR concept is that the flux is varied about an average value, whereas in the PM or conventional alternator the flux is periodically reversed, which means that the flux changes for a given magnet strength would be larger than in the VR alternator. When only low power levels are needed and efficiency is not critical, this feature may not be important. A schematic drawing of a VR alternator is shown in the figure.



An example of a variable-relunctance alternator. Every second winding is reversed so that when they are connected in series the voltages add. Parallel connections could be used to increase current. The shaded areas are the permanent magnets. If the magnets were mounted on the teeth of the rotor, the device would be a permanent-magnet alternator. The winding is shown symbolically. In practice conventional generator stator construction techniques would be used.

One way that the principles of the PM and VR alternators could be employed on freight cars without a mechanical coupling or drive system would be to attach the rotor assembly to the axle and either fully or partially surround it with the stator. A yoke containing a set of equally spaced teeth in the case of the VR alternator would suffice. The stator would have to be mounted such that it would be concentric with the axle and not move relative to it. The air gap betwen rotor and stator elements would have to be of the order of a few millimetres.

Another location for an alternator is on the end cap of the bearing assembly. The rotating end cap would be the rotor, with either permanent magnets or a crenellated surface, while the stator would be attached to the bearing adapter or bearing casing.

In either the axle or bearing-cap configuration, the variable reluctance concept has the advantage that the component attached to the rotating

member is simply a piece of magnetic material which will be rugged, reliable and inexpensive. The stationery coil and magnet assembly is amenable to sturdy construction and is sealable against the environment.

Some disadvantages, or problem areas, with these alternatives are:

- The mechanical tolerances between moving and stationary components is critical, although gaps of several millimetres should be permissible in a low-power generator.

- Implementation requires modification of the axle or the bearing components, depending on which version is used, as well as to the truck to provide a support for the stator.

- Permanent magnets tend to be demagnetized by repeated impacts. The vibration and mechanical shocks experienced at the bearings and axle of a truck would cause the permanent magnets to lose strength with time. That problem would have to be investigated further.

- The insulating effect of the stator assembly on the heat dissipated from the bearing and end cap would have to be considered.

Because of the extent of modification needed to install these alternators, the cost will be more than that of the components. In a large-scale retrofitting it is estimated that the total installed cost of a variable reluctance alternator would be about $500 per unit.

A device employing eight pole pieces and Alnico-5 magnets of cross-section 2.5 cm x 2.5 cm, with an air gap varying from 0.2 cm to 1 cm could produce tens of watts at a train speed of 40 km/h.